AN ANALYTICAL STUDY OF THE THERMAL EFFECTS OF HEAT REJECTION FROM POWER PLANTS TO COOLING PONDS

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

By
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to the
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CERTIFICATE

This is to certify that the thesis entitled "An Analytical Study of the Thermal Effects of Heat Rejection from Power Plants to Cooling Ponds" by Sheojee Tiwary is a record of work carried out under my supervision and has not been submitted elsewhere for a degree.

July 1978

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SHEOJEE TIWARY

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NOMENCLATURE

A	:	Surface area of cooling pond
A_e	:	Parameter defined by Eqn. (2.6a)
B	:	Parameter defined in Appendix I, Eqn. (I.2)
B_e	:	Parameter defined by Eqn. (2.6b)
c	:	Cloudiness factor
C	:	Parameter defined in Appendix I, Eqn. (I.3)
C_1	:	Parameter defined in Appendix I, Eqn. (I.19)
C_e	:	Time in days at which minimum surface equilibrium temperature occurs
d	:	Diameter or height of the intake stream
D	:	Parameter defined in Appendix I, Eqn. (I.4)
e	:	Partial vapour pressure
e_s	:	Saturated vapour pressure
h	:	Heat transfer co-efficient
H	:	Depth of cooling pond
h_w	:	Side convective heat transfer co-efficient
i,j	:	Index number for grid points
I	:	Number of elements from the surface of the cooling pond
k	:	Thermal conductivity
K	:	Surface heat exchange co-efficient
L	:	Side length of cooling pond
n	:	Total number of horizontal elements

p	:	Hydrostatic pressure
Q	:	Net heat loss from the surface
Q_a	:	Long wave radiation from the atmosphere
Q_{br}	:	Back radiation from water body
Q_c	:	Convective heat loss
Q_e	:	Evaporative heat loss
Q_i	:	Incident solar radiation
Q_r	:	Reflected radiation
Q_s	:	Effective solar radiation
Q_w	:	Long wave radiation from water body
Re	:	Reynolds number
R.H.	:	Relative humidity
t	:	Time in days
T	:	Temperature
T_a	:	Ambient temperature
T_b	:	Bottom temperature
T_e	:	Equilibrium temperature
T_s	:	Surface temperature
u	:	x-component velocity
U	:	Velocity of outfall and intake
V	:	Wind velocity
w	:	z-component or downward velocity
x,z	:	Cartesian co-ordinate.

$\bar{x}$, $\bar{z}$: Dimensionless Cartesian co-ordinate

GREEK SYMBOLS

β : Sky radiation factor

ε_H : Eddy diffusivity

ν : Eddy viscosity

ρ : Specific density

σ : Stefan Boltzman constant

ψ : Stream function

$\bar{\psi}$: Dimensionless stream function

SYNOPSIS

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In the present work, the steady state and transient, vertical temperature distribution in a cooling pond have been determined analytically. The effect of various governing parameters, such as ambient temperature, cloudiness, relative humidity, wind velocity, solar flux, eddy diffusivity and power plant capacity on the temperatures are studied in detail for a one dimensional model. The governing equations are solved numerically by finite difference method . A two-dimensional model, for the limiting cases of inviscid and creeping flow, neglecting variations in the lateral direction is also studied to determine the recirculation in the cooling pond. The study determines the effect on the intake temperature due to the heat rejected by a power plant into a water body.

CHAPTER 1

INTRODUCTION

1.1 The Problem:

Electric power has become a virtual necessity for the health, comfort and economic well being of the people. At present, a major part of the electric energy produced is generated by steam driven thermal power plants. Because of the potential impact on the quality of the air and water environment, due to heat rejection, the problem of setting up of large, new thermal power plants is becoming increasingly critical. One of the most crucial considerations is that of the disposal of the waste heat, inherent in the generating process keeping the efficiency of the energy generation system high and the effect on the environment low.

A characteristic of the operation of a steam driven thermal power plant is that a large flow of water is required in the condensers to condense the exhaust steam, from the turbine, as water. This keeps the temperature of condensation low, so as to maximize the energy conversion. The condensate is recirculated back to the boiler. In flowing through the condensers, the cooling water is generally heated by $6^{\circ}c$ to $9^{\circ}c$, depending upon the design of the plant. The amount

of waste heat discharged to the condenser is directly related to the efficiency of energy generation of the plant. An indication of the magnitude of the waste heat is the fact that even at the most efficient plants now in operation, the heat rejected is generally much greater than the heat equivalent of the electric energy generated. At a typical efficiency of 33% twice the amount of energy generated is rejected as waste heat.

The heat added to the water as it flows through the condensers must eventually be dissipated to the atmosphere. Many power plants use a cooling system for the dissipation of the waste heat, in which the water is taken from a river, lake, reservoir or the sea, passed through the condenser and then returned at a higher temperature to the water body. The added heat is subsequently dissipated by means of increased evaporation, back radiation and conduction to the atmosphere. The only consumption of water is that resulting from an increased evaporation in the water body due to the addition of heat.

At inland locations where natural streams or lakes of adequate size are not available and if suitable sites can be found, cooling ponds may be constructed to provide the cooling water needs. The structural and flow requirements for cooling ponds are essentially the same as that for natural water bodies. However, it does entail an additional expenditure in construction, which is of particular

significance for larger power plants. A natural attempt would, therefore, be to tap the natural resources such as lakes, rivers and the sea.

The cooling water is circulated between the condensers and the water body. This generates a flow field in the water body which results in a recirculation of the warm water, discharged at the outlet, to the cold water intake. This recirculation, which depends on the position of the intake and the outlet, the amount of heat rejected, flow rates, ambient conditions and the dimensions and characteristics of the water body, raises the temperature at the intake and thus lowers the efficiency, of the power plant, which is linked, from thermodynamic considerations to the temperature at which heat is rejected, being lower for a higher temperature.

Most of the water bodies, under Indian conditions are generally stratified over a large part of the year. This implies that a heated upper layer lies over a colder layer. This is a stable situation since colder layers are heavier than heated layers. Unless forced by restrictions on the outfall temperature from the power plant, the heated discharge is usually floated over the surface of the stratified water body, in order to obtain a high surface temperature, which gives rise to a high rate of heat loss at the surface and minimum effect on the water body. At the same time, the intake is located below the interface between the two layers, termed as the thermocline, so as

to employ the lowest available temperature of cooling water, for increased efficiency of energy generation. A general sketch of the problem of recirculation is shown in Fig. 1.

1.2 Review of Previous Work:

Initially, this area was largely considered due to the environmental effects arising from heat rejection. Recently, the need of a fluid flow and heat transfer analysis has been realised, in an attempt to improve the power plant efficiency. A comprehensive review of the literature with extensive references is given by Jaluria, Variyar and Mehta (1976).

Raphael (1962) developed a procedure for predicting the temperature of various water bodies, such as shallow lakes, flowing streams and detention reservoirs, from weather records, inflow and outflow characteristics, the surface area and the volume of the water body. He assumed that the thermocline is absent and the water is so stirred by wind or internal currents that the temperature is uniform throughout. Delay and Seaders (1966) developed a mathematical model for predicting temperatures in rivers and reservoirs. They computed the net monthly energy exchange from the reservoir and then distributed it vertically so that the resulting temperature gradients approximated the standard for each month. Dake and Horleman (1969) developed a theoretical model for the time dependent vertical temperature distribution in a deep lake, during the yearly cycle. They took a heat-flux

balance at the water surface, which accounts for back radiation and evaporative loss as a boundary condition.

Tamai, Wiegel and Tornberg (1969) realised that the main problem, in the design of cooling water systems for thermal power plants, is the determination of the nature of mixing of the warm water discharge, so as to find methods to minimize the recirculation of the waste heat. With this in mind, they performed several experiments, on the mixing of buoyant flows, discharged horizontally at the surface of a body of water, in the laboratory. They also collected data, from a number of sources, on the cooling water capacities of thermal power plants, along with the flow characteristics, and compared them with the experimental values. Brown (1970) has discussed the various methods of waste heat disposal and has emphasised the need to develop improved and less costly cooling devices. Stefan (1970, 1972) showed that the flow and the cooling of a warm water surface layer can be represented by a physical model, if the inflow and outflow of water and the atmospheric conditions, it is exposed to, are controllable. He simulated the phenomena of mixing at the outlet, stratification and the surface heat transfer through the use of physical models. He also described an experimental design to simulate a heated water discharge from a channel, into a deep lake for lateral spread.

Moore and Jaluria (1971, 1972) studied the thermal effects of power plants on lakes, in terms of its temperature cycle. They

developed a one-dimensional model based on the assumption that a Richardson number is constant at the base of any stratified layer. This gave a constant heat flux across the thermocline. The model is then perturbed in terms of this heat flux, as well as the thermal diffusivity to give the power plant impact on a given lake. They computed the change in the summer maximum, winter minimum, stratification and overturn, or destratification, temperatures and time of occurrence.Grubert and Abbott (1972) gave the mathematical formulation of nearly horizontal stratified flows, in terms of partial differential equations and their characteristics. They have also shown that the characteristic directions in a stratified fluid devide into pairs, each pair being associated with a fluid layer. Hindley and Miner (1972) observed that the temperature distribution in a cooling water body, being employed for a power plant, is dependent upon the manner in which the heated effluent mixes with the receiving water body and upon the rate of heat exchange between the water surface and the atmosphere. They found that, far from the receiving end, where mixing is nearly complete, the dominant cooling mechanism is heat exchange with the atmosphere. The rate of this cooling is directly proportional to the surface heat exchange co-efficient, which is in turn a function of several environmental variables, particularly the wind velocity.

Based upon the assumption of horizontal isotherms, at all times, Huber, Harleman and Ryan (1972) developed a mathematical model,

for determining the vertical temperature distribution in stratified reservoirs, which includes the effects of heat sources and sinks at the boundaries, internal absorption of solar radiation and heat transport by convection and diffusion. Miyazaki (1974) studied the heated two-dimensional jet discharge at the water surface. He carried out an analysis at various Richardson numbers and calculated the velocity and temperature distributions. Snider and Viskanta (1975) carried out an analysis for the time dependent thermal stratification in the surface layers of stagnant water due to solar radiation. They used finite difference methods to obtain the transient temperature distribution, by solving the one-dimensional energy equation, for combined conduction and radiation energy transfer mechanisms.

Jaluria, Variyar and Mehta (1976, 1977) developed a mathematical model to predict the temperature and velocity profiles in a body of water, due to the basic mechanisms in the presence of winds, cloudiness, back radiation etc. They computed the equilibrium average surface temperature, which is defined as the temperature attained by the surface, if the ambient conditions are held constant at specific values, and studied the heat transfer mechanism at the surface in detail. They also developed a more generalized model, considering convection effects caused by the outflow and intake of cooling water and the heat addition from the power plant. They studied certain specific, simplified, one and two-dimensional models in detail. The work concentrated largely

on steady state models and not much work has been done on the transient behaviour, which forms an important consideration in the present study, as outlined below.

1.3 Present Work:

In the present work, a one-dimensional mathematical model, in the form of finite difference equations, has been developed, to determine the vertical temperature distribution in the cooling pond. Both the steady state and transient, or time dependent, cases are studied in detail, for a natural lake, as well as for a lake, or cooling pond, with heat rejection from power plants.

The net surface heat exchange is computed by using a method similar to that outlined by Jaluria, Variyar and Mehta (1976) mainly for Indian conditions, with respect to the ambient conditions, such as solar flux, wind speed, ambient temperature, etc. The equilibrium average surface temperature is determined, which is employed in the computation of the vertical temperature distribution. The effects of various governing parameters such as ambient temperature, cloudiness, relative humidity, back radiation, solar flux, heat discharge from power plants, flow rates etc. on these results are studied in detail, to provide the first step in the design of such systems.

The work considers the transient temperature variation in detail, developing suitable models for stratification and destratification of the water body. The effect of the power plant on the

intake temperature rise is determined and the dependence of this effect on the various parameters is outlined. It is found that the water body is stratified for most part of the year. The power plant tends to raise the temperature level and change the stratification cycle of the water body. The effect of turbulence, is considered on the basis of the eddy diffusivity and this is taken as a parameter, whose effect is also studied. The work is of considerable importance in the design of cooling water systems, with respect to flow rates, heat input, locations of intake and outfall, etc.

A two-dimensional model, neglecting variations in the lateral direction, is also developed to determine the recirculation in the cooling pond . The model is studied for the extreme cases of inviscid and creeping flow. The resulting velocity field is determined and the general nature of the flow is discussed.

All the computations were carried out on IBM 7044 Computer, at IIT/Kanpur. The various meteorological data needed for the study were obtained largely from Indian Meteorological Department and partly from the analysis given by Raphael (1962).

CHAPTER 2

THEORETICAL MODELS AND METHOD OF SOLUTION

The behaviour of a water body, which acts as a cooling water source for a power plant, is determined, to a large extent, by the nature of its interaction with the environment, to which it ultimately dissipates the heat added by the power plant. Hence, in developing an analytical model for a cooling pond, the mathematical representation of the various mechanisms underlying its interaction with the environment is of considerable importance. The basic features of an analytical model for the lake may now be outlined as follows:

a) A finite pond or lake.

b) No energy transfer across its sides and bottom i.e., energy transfer occurs only at its surface and at the intake and outfall for the cooling water of the power plant. This assumption is adequately supported by various investigations.

c) An idealized configuration of vertical sides and flat horizontal base would be considered initially. This could be eventually modified to consider, as close as possible, the exact topology of a given lake.

d) The outfall at the surface, while the intake at the bottom of the lake. This implies that the outfall enters the lake with the

smallest possible disturbance. This is applicable in most practical applications.

e) Temperature variation in the natural lake is only in the vertical direction, the horizontal gradients being neglected.

f) Ambient conditions are functions of time, though they may be taken as specific values over small time periods during the year.

2.1 Energy Exchange at the Surface:

The energy exchange at the surface, is due to various heat transfer mechanisms outlined below:

a) Radiation from the Sun and from the Atmosphere:

At a point outside the atmosphere of the earth, radiant energy is received from the sun, on a surface normal to its rays, at a rate of approximately 1165 K.cal/hr/sq.m. This value, called the "Solar Constant", fluctuates slightly during the course of the year because of sunspots and variation in the distance between the earth and the sun. A plane, normal to the rays of the sun at the surface of the earth receives considerably less energy, as compared to the solar constant because moisture, gases and solid particles in the air scatter and absorb much of the incident radiation. Although much of the direct radiant energy is lost, some of this energy is recovered as diffuse radiation.

Of the total quantity of the direct, or short weve, radiation that reaches the surface of a lake, a portion is returned unchanged due to reflection at the surface and scattering by bubbles and suspended particles immediately below it. However, for practical engineering computations, solar radiation and reflected radiation can be combined in one function, $(Q_i - Q_r)$ or :

$$Q_s \text{ (effective absorbed solar radiation)} = Q_i - Q_r \qquad (2.1a)$$

If , c , is the average cloud cover, in tenths of sky covered, the net short-wave radiation is obtained from the correlation given by .

$$Q_s = (1 - 0.0071\, c^2)\,(Q_i - Q_r) \qquad (2.1b)$$

b) <u>Back Radiation</u>:

Effective back radiation may be defined as the difference between Q_w , the longwave radiation leaving a body of water, and Q_a , the longwave radiation from the atmosphere being absorbed by the body of water. Atmospheric radiation does not follow any simple law as it is a function of many variables, such as the distribution of moisture, temperature, ozone, carbon dioxide, etc. Thus, this has been found to be dependent on cloud height, as high, middle and low clouds, and the amount of cloud, as scattered cloud, broken cloud and over cast. However, as most weather observations give cloud amount in tenths of sky obscured, the variation of the atmospheric radiation factor has been given as a function of cloud amount and vapour

pressure by Raphael (1962). The effective back radiation, Q_{br} can be computed as,

$$Q_{br} = Q_w - Q_a = 0.970 \times \sigma (T_s^4 - \beta T_a^4) \qquad (2.2)$$

where, σ is Stefan-Boltzman Constant, T_s is absolute water surface temperature, T_a is absolute ambient temperature and β is sky radiation factor, tabulated by Raphael (1962).

c) Convection:

Sensible heat is convected to or from a body of water whenever a temperature difference exists between air and water. The basic equation for the convection heat transfer, Q_c , from the water surface to the air is,

$$Q_c = h \ (T_s - T_a) \qquad (2.3)$$

where h is the surface heat transfer coefficient. The value of h is largely dependent on the condition of the air in contact with the water and hence it is a function of the wind velocity, its temperature, direction and turbulence level, etc. The following correlation, by Wada (1968), has been found to be most suitable for conditions relevant to India.

$$h = 2.77 \times 10^{-3} \ (0.48 + 0.272 \ V) \ \text{K.cal/m}^2\text{.sec.} \ ^\circ\text{c} \qquad (2.3a)$$

where V is the wind velocity along the water surface in meter/sec.

d) Evaporation:

When the vapour pressure of ambient air is less than the

saturated vapour pressure, at the water surface temperature, water evaporates into the air, removing heat from the water mainly due to the energy required to evaporate the water and to a small extent, by the secondary heat transfer due to the sensible heat contained in the water removed by evaporation. The correlation used to calculate the heat transfer by evaporation is obtained from the work of Hindley and Miner (1972). This is given as,

$$Q_e = 2h\left[e\,(T_s) - e\,(T_a)\right] \tag{2.4}$$

where, $e(T_s)$ is the partial vapour pressure at water surface temperature in mm of hg, $e(T_a)$ is the partial vapour pressure at ambient temperature in mm of hg and h is the heat transfer coefficient defined by Eqn. (2.3a). Also,

$$e(T_a) = e_s(T_a) \times \text{R.H.} \tag{2.4a}$$

where, $e_s(T_a)$ is the saturated vapour pressure at ambient temperature and R.H. is the relative humidity at ambient temperature.

The above relationship can also be obtained by considering the analogy between heat and mass transfer and the corresponding Prandtl and Schmidt numbers. Therefore, the heat loss from the surface is given by ,

$$Q = Q_e + Q_{br} - Q_s + Q_c \tag{2.5}$$

The surface equilibrium temperature T_e, may often be represented approximately as a sinusoidal variation over the year. This approximation has been used extensively by many investigators, see,

for instance, the representation of Moore and Jaluria (1972) as:

$$T_e = A_e - B_e \cos\left[\frac{2\pi(t - C_e)}{365}\right] \tag{2.6}$$

where, $$A_e = \frac{(T_e)_{max.} + (T_e)_{min.}}{2} \tag{2.6a}$$

$$B_e = \frac{(T_e)_{max.} - (T_e)_{min.}}{2} \tag{2.6b}$$

and C_e is time in days at which the minimum surface equlibrium temperature occurs, where t is time in days.

The rate of net heat loss from the surface, Q, is given as:

$$Q = K\,(T_s - T_e) \tag{2.7}$$

where, K is the surface heat exchange coefficient and T_e, the surface equilibrium temperature represented as a sinusoidal wave. In the above equation, K and T_e are dependent on ambient conditions and may be determined for a given lake by a detailed study of Q and T_e in terms of various mechanisms, as outlined above.

2.2 One Dimensional Models:

Physically, a one dimensional model represents the circumstance when the lateral mixing in the lake, or the cooling pond, is so vigorous that only vertical exchange of heat and mass need be considered. It has been found by Raphael (1962) that the eddy diffusivity in the vertical direction, for stratified water bodies, is around one-hundredth the value in the horizontal direction. Therefore, horizontal

mixing is much more vigorous, mainly due to the buoyancy forces resulting from the temperature dependent density differences. A uniform temperature in the horizontal plane may be assumed over a finite area, of the water body, where most of the flow occurs. A convective loss from the side to the surrounding water medium, at the temperature for the natural lake, may be assumed. In actual practice, the recirculation would essentially occur over a portion of the water body and energy would be lost to the neighbouring water through a similar induced motion, arising due to the entrainment requirements of the recirculating flow.

For a one dimensional model, since temperature variation exists only in the vertical direction, the boundary conditions have to be specified at the surface and at the bottom, with the convective loss, if any, to the neighbouring fluid, taken as an energy loss from each fluid element. The theoretical model is developed for the steady state, as well as for, the transient, as outlined below:

2.2.1 Steady State:

A side loss model with energy input from a power plant is considered. Neglecting density variations, the continuity and energy equations yield the following, the momentum equation being only the hydrostatic pressure variation equation:

$$\frac{dw}{dz} = 0 \tag{2.8}$$

$$\epsilon_H \frac{d^2T}{dz^2} - w\frac{dT}{dz} - \frac{h_w(T - T_e)}{\rho C_p L} = 0 \tag{2.9}$$

with the conditions :

$$T = T_s \quad \text{and} \quad w = w_0 \text{ at } z = 0 \tag{2.9a}$$

$$T = T_b \quad \text{and} \quad w = w_0 \text{ at } z = H \tag{2.9b}$$

$$w\left[(T_b + \Delta T) - T_s\right] + \epsilon_H \frac{dT}{dz} - \frac{Q}{\rho C_p} = 0, \text{ at surface} \quad \ldots \tag{2.9c}$$

where, w is the vertical velocity in the cooling pond, ϵ_H is the eddy diffusivity, h_w the side convective heat transfer coefficient, T_b the bottom element temperature of the cooling water body, ΔT the difference between outlet and inlet temperature of condenser cooling water, L the side length of the cooling water body over which the temperature is taken as uniform and A, the top surface area of the cooling pond. Here ΔT is taken as a known quantity, h_w is varied as a parameter and iteration is carried out till the temperatures does not vary from one iteration to the other. This final profile gives the values of T_s and T_b. The velocity w_0 is known from inflow.

2.2.2 Transient:

The side loss is not considered in the transient model, taking the lake to be at uniform temperature horizontally. The energy equation for the natural lake, without power plant, and for

the cooling pond, with a power plant, is obtained as discussed below:

a) Natural Lake:

The governing one dimensional energy equation is :

$$\frac{\partial T}{\partial t} = \epsilon_H \frac{\partial^2 T}{\partial z^2} \tag{2.10}$$

with the conditions :

$$T = T_s \quad \text{at} \quad z = 0 \tag{2.10a}$$

$$T = T_b \quad \text{at} \quad z = H \tag{2.10b}$$

$$\epsilon_H \frac{\partial T}{\partial z} - \frac{Q}{\rho c_p} = 0 \text{ , at the surface} \tag{2.10c}$$

b) Cooling Pond:

The governing one dimensional energy equation is :

$$\frac{\partial T}{\partial t} = \epsilon_H \frac{\partial^2 T}{\partial z^2} - w \frac{\partial T}{\partial z} \tag{2.11}$$

with the conditions:

$$T = T_s \quad \text{and} \quad w = w_0 \quad \text{at} \quad z = 0 \tag{2.11a}$$

$$T = T_b \quad \text{and} \quad w = w_0 \quad \text{at} \quad z = H \tag{2.11b}$$

$$w\left[(T_b + \Delta T) - T_s\right] + \epsilon_H \frac{\partial T}{\partial z} - \frac{Q}{\rho c_p} = 0, \text{ at the surface} \quad \ldots\ldots \tag{2.11c}$$

2.2.3 Method of Solution:

The cooling water body is divided into n horizontal elements (Fig. 1), each of depth Δz. The governing differential

equations are written in their finite difference form, see Appendix I. Separate finite difference equations are developed for the surface, bottom and intermediate elements. These finite difference equations are solved by iterative technique. Iteration is continued until the convergence is obtained, indicated by the difference between $T^{r+1}(I)$ and $T^{r}(I)$ becomes smaller than a small specified value for all values of I considered, where r is the number of iteration and I the number of the element from the top. The initial guess $T^{0}(I)$ was found to affect the convergence significantly, the closer the initial guess is to the final solution, the faster is the convergence, as expected. The following initial guess was employed,

$$T^{0}(I) = T_e \text{ , for all } I \tag{2.12}$$

For the transient solution, the analysis begins on January Ist., when the lake is in a fully mixed, or isothermal, state and the solution is carried out over the year. The iteration procedure is carried out till the temperatures remain unchanged from one year to the other.

2.3 Two Dimensional Recirculation Models:

A two dimensional model (Fig. 1) for the study of recirculation assumes complete mixing in one direction. A vertical model with good lateral mixing is considered. This situation frequently arises in narrow lakes and rivers. The intake and outfall are considered to be in the same vertical plane. The basic governing

equations for the flow field, for constant fluid properties, eddy viscosity and diffusivity, and neglecting buoyancy effects,are

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{2.13}$$

$$u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu_{mx}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{2.14}$$

$$u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \nu_{mz}\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial z^2}\right) \tag{2.15}$$

$$u\frac{\partial T}{\partial x} + w\frac{\partial T}{\partial z} = \epsilon_H\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{2.16}$$

where u is the velocity component in x-direction, w the velocity component in z-direction, ν_{mx} the eddy viscosity in x-direction, ν_{mz} the eddy viscosity in z-direction, and ϵ_H the eddy diffusivity.

The flow field can be solved independent of the energy equation. The equations are quite complex and require simplifications before a solution may be attempted.

2.3.1 Method of Solution:

It is assumed that the eddy viscosities in both the directions are equal and given by,

$$\nu_{mx} = \nu_{mz} = \nu$$

we may now eliminate the pressure termsfrom Equations (2.14) and (2.15), and the resulting single equation is obtained as,

$$u\left(\frac{\partial^2 u}{\partial z\,\partial x}-\frac{\partial^2 w}{\partial x^2}\right)+w\left(\frac{\partial^2 u}{\partial z^2}-\frac{\partial^2 w}{\partial x\,\partial z}\right)=\nu\left(\frac{\partial^3 u}{\partial z\,\partial x^2}+\frac{\partial^3 u}{\partial z^3}-\frac{\partial^3 w}{\partial x^3}-\frac{\partial^3 w}{\partial x\,\partial z^2}\right) \quad (2.17)$$

A stream function ψ is now introduced, in the above equation, so that it satisfies the continuity equation and is given by,

$$u=\frac{\partial\psi}{\partial z} \quad (2.18)$$

$$w=-\frac{\partial\psi}{\partial x} \quad (2.19)$$

Thus the Equation (2.17) in terms of stream function ψ is given by,

$$\frac{\partial\psi}{\partial z}\frac{\partial}{\partial x}(\nabla^2\psi)-\frac{\partial\psi}{\partial x}\frac{\partial}{\partial z}(\nabla^2\psi)=\nu(\nabla^4\psi) \quad (2.20)$$

where,

$$\nabla^2\psi=\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial z^2} \quad (2.20a)$$

The above equation may be expressed in terms of dimensionless parameters, particularly the Reynolds number, defined as:

$$Re=\frac{Ud}{\nu} \quad (2.20b)$$

where, U is the average intake velocity, d is the diameter or height of the intake stream, and ν is eddy viscosity.

Thus, the equation (2.20) is expressed as,

$$\frac{\partial\bar{\psi}}{\partial\bar{z}}\frac{\partial}{\partial\bar{x}}(\nabla^2\bar{\psi})-\frac{\partial\bar{\psi}}{\partial\bar{x}}\frac{\partial}{\partial\bar{z}}(\nabla^2\bar{\psi})=\frac{1}{Re}(\nabla^4\bar{\psi}) \quad (2.21)$$

where, ψ is non-dimensionalized by Ud, to obtain $\bar{\psi}$ and x and z by H.

Now the Equation (2.20) is solved for two extreme cases :

a) When Reynolds number is very high , the viscous terms may be neglected. The fluid then behaves as inviscid. For an inviscid flow the stream function satisfies the Laplace equation, which is given by,

$$\nabla^2 \psi = 0 \tag{2.22}$$

with the following conditions,

$$\begin{aligned}
x &= 0, \quad 0 < z < d \ , \ \frac{\partial \psi}{\partial z} = U \\
x &= 0, \quad H - d < z < H \ , \ \frac{\partial \psi}{\partial z} = - U \\
x &= 0, \quad d \leq z \leq H - d, \ \frac{\partial \psi}{\partial z} = 0 \\
x &= L, \quad 0 < z < H \ , \ \frac{\partial \psi}{\partial z} = 0 \\
z &= 0, \quad 0 \leq x \leq L \ , \ \frac{\partial \psi}{\partial x} = 0 \\
z &= H, \quad 0 \leq x \leq L \ , \ \frac{\partial \psi}{\partial x} = 0
\end{aligned} \tag{2.22a}$$

This gives the standard inviscid flow boundary conditions in terms of constant stream function on the boundaries, as given in Fig. 13.

b) When Reynolds number is very small, i.e., the fluid behaves as highly viscous. This is true for very low velocities generally encountered in such flows, the problem being known as "creeping flow". Thus the viscous terms dominate and the inertia terms are neglected. This gives Eqn. (2.20) as,

$$\nabla^4 \psi = 0 \tag{2.23}$$

with the following conditions,

$$z = 0,\ 0 \leqslant x \leqslant L\ ,\ \frac{\partial \Psi}{\partial x} = 0,\ \frac{\partial^2 \Psi}{\partial x^2} = a,$$ where, a is zero when the surface shear force is absent.

$$z = H,\ 0 \leqslant x \leqslant L\ ,\ \frac{\partial \Psi}{\partial x} = \frac{\partial \Psi}{\partial z} = 0$$

$$x = 0,\ d \leqslant z \leqslant H - d\ ,\ \frac{\partial \Psi}{\partial x} = \frac{\partial \Psi}{\partial z} = 0 \qquad (2.23a)$$

$$x = 0,\ 0 < z < d\ ,\ \frac{\partial \Psi}{\partial z} = U$$

$$x = 0,\ H - d < z < H\ ,\ \frac{\partial \Psi}{\partial z} = - U$$

$$x = L,\ 0 \leqslant z \leqslant H\ ,\ \frac{\partial \Psi}{\partial z} = \frac{\partial \Psi}{\partial x} = 0$$

The equations (2.22) and (2.23) are solved by finite difference methods. A rectangular mesh as shown in Fig. 1 is used for this purpose. At every point in the interior of the considered region, a finite difference relation is setup in accordance with the above equations. The various partial derivatives involved are approximated by central difference approximations. Separate equations are written for the elements at the intake and outfall. The surface elements will also require a separate equation, particularly for the energy equation. Thus the finite difference equations are solved by iterative techniques. Thus, starting from the initial guess $\bar{\Psi}^{0}_{i,j}$, we determine the successive iterates $\bar{\Psi}^{1}_{i,j}$, $\bar{\Psi}^{2}_{i,j}$ ...... $\bar{\Psi}^{r}_{i,j}$.... from the general formulae given in Appendix I. Iteration is continued until the convergence is obtained, i.e., difference between $\bar{\Psi}^{r+1}_{i,j}$ and $\bar{\Psi}^{r}_{i,j}$ becomes smaller than the specified value for all values of i,j considered. The following initial guess is used,

$$\bar{\Psi}^{0}_{i,j} = 0 \text{ for all } (i,j) \qquad (2.24)$$

CHAPTER 3

RESULTS AND DISCUSSION

This chapter deals with the numerical results obtained from the thermal analysis of a cooling pond. The stratification of the cooling pond is largely dependent on the net surface heat exchange, which in turn is a function of the surface temperature. The net energy lost by the surface, Q, as a function of the surface temperature and the wind velocity, is computed by a numerical evaluation of the various components of energy exchange and is shown in Fig. 2. The curve shows that at low surface temperatures, the change in wind velocity does not have much effect on the surface heat exchange, as compared to that at high surface temperatures. At these high values, a small change in the wind velocity, gives a considerable amount of increase in the heat lost at the surface. Energy loss increases with surface temperatures, as expected.

The average surface equilibrium temperature, T_e, which is defined as the surface temperature at which the net heat exchange from the surface is zero, is computed for different sets of meteorological parameters. In Fig. 2, the intercept of the curves on the x-axis, gives the value of the equilibrium temperature for various conditions. The results, for varying ambient conditions, are shown

in Fig. 3. For each variable, the remaining variables are kept constant at the values indicated as typical values in the figure. It is found that the surface equilibrium temperature, T_e , increases with an increase in the ambient temperature, as expected, and also with the relative humidity , since it reduces the evaporation, therefore requiring a higher surface temperature for energy balance. It is also seen that T_e decreases with an increase in the wind velocity and in the cloudiness factor. This indicates that the net heat gain by the surface increases with an increase in the ambient temperature and a decrease in cloudiness factor, since clouds cutdown on the solar flux received. Also, the net heat loss from the surface increases with an increase in wind velocity, due to greater evaporation and convective loss, and a decrease in the relative humidity. It is also observed that the equilibrium temperature is more sensitive to ambient temperature than to the other parameters, such as wind velocity, relative humidity and the cloudiness factor etc.

Fig. 4 shows the steady-state vertical temperature distributions in the cooling pond at various times during the year. It is observed that the vertical temperature gradient is slightly more in winter than in summer. This is mainly due to an increase in the net surface heat gain during summer, which is conducted and convected to lower layers of the cooling water body. The steady-state temperatures are higher during summer months as expected. In this case, a uniform

temperature in the surrounding fluid is assumed. The profiles for different values of h_w, the side loss heat transfer co-efficient, are computed and plotted in Fig. 5 for summer. It is seen that as the value of h_w increases, the temperature gradient increases at the top. With increasing h_w, a greater percentage of the rejected heat is lost to the neighbouring fluid and a greater temperature variation with depth results. Similarly Fig. 6, shows the steady-state temperature profiles for different values of ϵ_H., the eddy diffusivity. It is also found that the profile becomes steeper with an increase in the value of ϵ_H, since this also results in greater loss to the neighbouring fluid. These results were obtained with a constant value of h_w and ϵ_H, over the entire depth. However, the temperature profile was also studied for h_w and ϵ_H as functions of the depth, decreasing with an increase in depth. But these temperature profiles were found to be quite close to the previous temperature profiles for the variation studied. This steady-state model simply gives the temperature level at various times during the month and the general nature of the profile. A stratified profile in the surrounding fluid may also be used for more realistic results.

The transient case is now considered. The time step-size is taken as one day and the ambient conditions were taken at their average values during this time interval. Since the ambient conditions vary over the year, the water body responds to heat rejection

from the power plant differently at different times during the year. The main problem is that the water body does not reach a steady-state and its temperature profile continues to vary during the year. The transient behaviour of a natural lake, without heat rejection, for the measured meteorological conditions at a location near Kanpur is shown in Figs. 7-9. Fig. 7 shows the transient vertical temperature distributions in the natural lake at various times during the year. Fig. 8 shows the variation of the bottom and surface temperatures during the year. The temperature profiles indicate that during early winter, as around the Ist. of January, the water body is in a fully mixed condition. With the passage of time, the water body loses energy and its temperature decreases until the winter minimum temperature is obtained. This occurs sometime in early February for these conditions. After this, the water body starts gaining energy and stratification occurs. Then, the surface temperature increases rapidly while the bottom temperature increases much more gradually, since the pond gains energy at the surface. This energy is gradually transferred to the bottom layers. The vertical temperature profiles in the cooling pond become more and more steep at the surface. This continues until the surface temperature attains the summer maximum temperature. After this, the cooling pond starts loosing heat. This gives rise to an isothermal top layer as seen in Fig. 7. The surface temperature decreases rapidly due to this loss of energy, while the

bottom temperature increases slowly due to the gain in energy from the hotter upper layers. Destratification occurs in early winter and the water body becomes fully mixed, i.e., the isothermal state is reached. The water body continues to lose heat beyond this point and its temperature decreases to a value close to that at the beginning of the year and the cycle continues. The nature of profiles at various times is apparent in Fig. 7 and the transient behaviour in Fig. 8.

The occurrence of stratification is delayed by a few days, as shown in Fig. 8 and its effect on the bottom and surface temperatures, is studied. This relates to the delay due to the wind induced mixing of the water body. It is found that the surface temperature remains nearly unchanged, while the bottom temperature increases with an increase in the delay period. A delay in the onset of stratification implies an equal distribution, of the net heat gain at the surface, vertically throughout the depth. Thus during that period, the surface temperature will be less than the surface temperature obtained without a delay and the bottom temperature will be larger. This affects the yearly temperature cycle of the lake and the bottom temperature increases due to the greater input of energy into the bottom layers.

Now, the net heat exchange from the surface is computed by considering a sinusoidal variation of the surface equilibrium

temperature, T_e , and using Eqn. (2.4). The yearly surface and bottom temperature variation, for a natural lake, and the variation of the surface equilibrium temperature is plotted in Fig. 9, for two values of K, the surface heat exchange co-efficient. It is found that with an increase in the surface heat exchange co-efficient, the bottom temperature decreases throughout the year. This change in the bottom temperature is maximum during early stratification and minimum near the destratification process. The surface temperature decreases during winter and increases during summer. Since the equilibrium temperature is less than the average surface temperature during winter and is more than the average surface temperature during summer, the water body will lose heat in winter and gain heat in summer. This surface heat exchange will increase with an increase in surface heat exchange co-efficient. This causes the lake to gain more energy in summer, resulting in higher temperatures and to lose more energy in winter, resulting in lower temperatures.

The basic effect of heat rejection would be to increase the surface temperature, which varies over the year for the natural lake. It will also affect the bottom temperature due to energy transfer in the water body and the intake water temperature is expected to rise. Fig. 10 shows the surface and bottom temperature variation for the natural lake as well as for the cooling pond, i.e., the lake with a power plant. The difference between these two is mainly due to the

rejection of waste heat from the power plant to the cooling pond. The temperature level increases as expected. The effect of wind velocity, on the bottom and surface temperature profiles of the natural lake is also studied and plotted in Fig. 10. It is found that with increase in wind velocity the temperature of the cooling water body decreases throughout the year at all points. It indicates that the net heat loss from the surface increases with increase in wind velocity, as expected. The effect of the power plant capacity and of the eddy diffusivity on the cooling water intake temperature is also studied and plotted in Figs. 11-12. The effect of power plant capacity, i.e., of the heat rejected, on the intake temperature is shown in Fig. 11. This indicates that with an increase in heat rejection, the intake temperature increases. This is mainly due to an increase in the heat, which must be rejected by the lake to the atmosphere. It also gives the flow rate impact on the intake temperature, if the temperature rise in the condenser Δt is kept constant. The heat addition due to power plant is dependent upon w, the downward velocity in the cooling pond and Δt, the temperature rise in the condenser, and a change in either gives a similar effect. Fig. 12 shows the effect of eddy diffusivity, or of increased turbulent mixing in the lake, on the intake temperature. It is found that with an increase in the value of the eddy diffusivity, the intake temperature increases during winter and decreases during summer. With an

increase in eddy diffusivity the mixing in the water body increases and this increases the rate of heat transfer between the surface and the bottom layers of the water body. Thus a larger amount of the energy gained in the summer is transferred to the bottom layers which, therefore, reflects a higher temperature in winter, due to the transient lag. More energy is similarly lost by the bottom layers in winter and this is reflected as a lower temperature in summer, for a higher value of eddy diffusivity.

The two dimensional vertical flow pattern in the cooling pond is also studied and plotted in Figs. 13-14. Fig. 13 shows the stream line distribution for inviscid flow, while Fig. 14 shows the stream line distribution for creeping flow. It is found that in inviscid flow a greater portion of the cooling water body is affected by the flow as compared to that in creeping flow where only a small portion of the water body is found to have flow at all. The part of the water body away from the outfall of the hot condenser water is found to be undisturbed and thus in creeping flow analysis, this part of the cooling pond does not play a significant role in heat rejection. The flow pattern in both the cases is more or less as expected. For a very big lake, the area where the flow exists must be determined for a proper understanding of the flow mechanisms. The problem may now be solved for the temperature field. It is expected that the temperature will decrease vertically downwards and away from the outfall. The adiabatic condition is to be employed at the walls and the surface energy exchange at the surface.

CHAPTER 4

CONCLUSIONS

From the discussions in Chapter 3, it is noted that the results obtained are physically reasonable. The steady state profiles show that the water body is nearly stratified throughout the year, while the transient profiles indicate that the cooling water body remains in fully mixed condition during early winter and in stratified condition during rest of the year. This is mainly due to the time dependent nature of the water body. The transient profiles obtained by taking a sinusoidal variation of the surface equilibrium temperature are found to be similar to those obtained by considering the surface equilibrium temperature as a function of the exact net heat exchange from the surface. The equilibrium temperature in the latter case is defined as the surface temperature at which the net heat exchange from the surface, at the given ambient conditions, is zero. The effect of the heat rejection from a power plant is found to be a rise in the intake temperature, which shows a greater change for a higher power plant capacity, as expected. The effect is found to be larger in summer, due to the higher ambient temperature, which makes the additional heat loss more difficult. The effect of a variation in power plant capacity, in turbulent

mixing, as reflected in the eddy diffusivity, and in ambient conditions is studied. The results obtained provide guidelines for limiting power plant capacity for a main water body and all indicated the expected recirculation effect on intake temperature.

The two-dimensional flow pattern, in the cooling pond has also been studied for the two limiting cases of inviscid and creeping flow. The former applies for large outfall velocities and the latter for small values. The present work can also be extended for other flows that may arise in practice. The temperature distribution, which is closely associated with the flow pattern may also be considered for future work.

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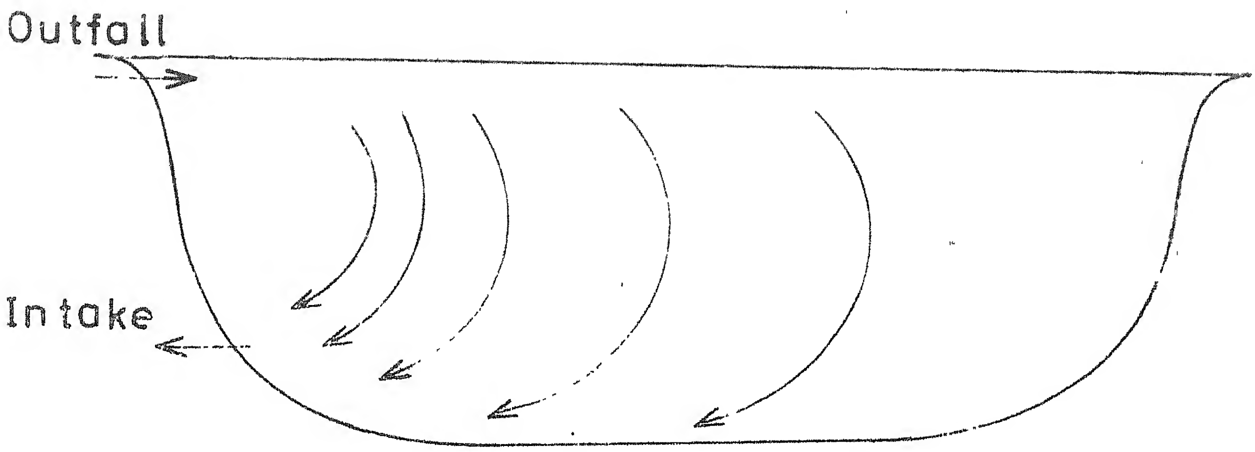

Fig. 1 (a) Flow pattern in recirculation

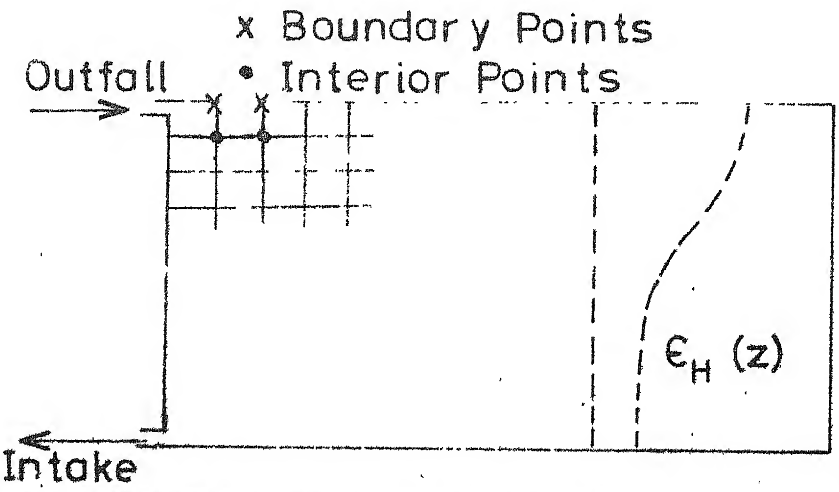

Fig. 1 (b) Two dimensional flow

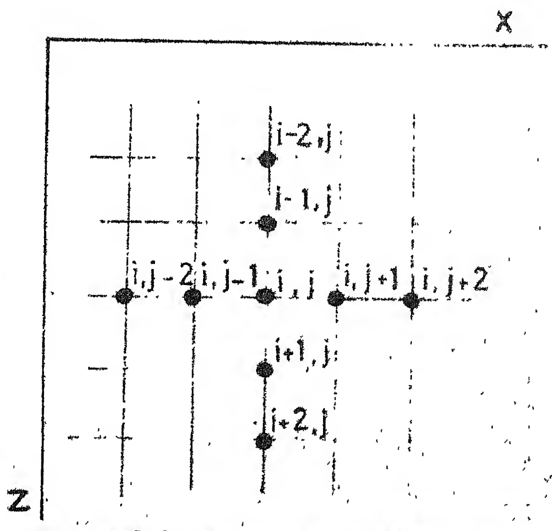

Fig. 1 (c) Finite difference grid

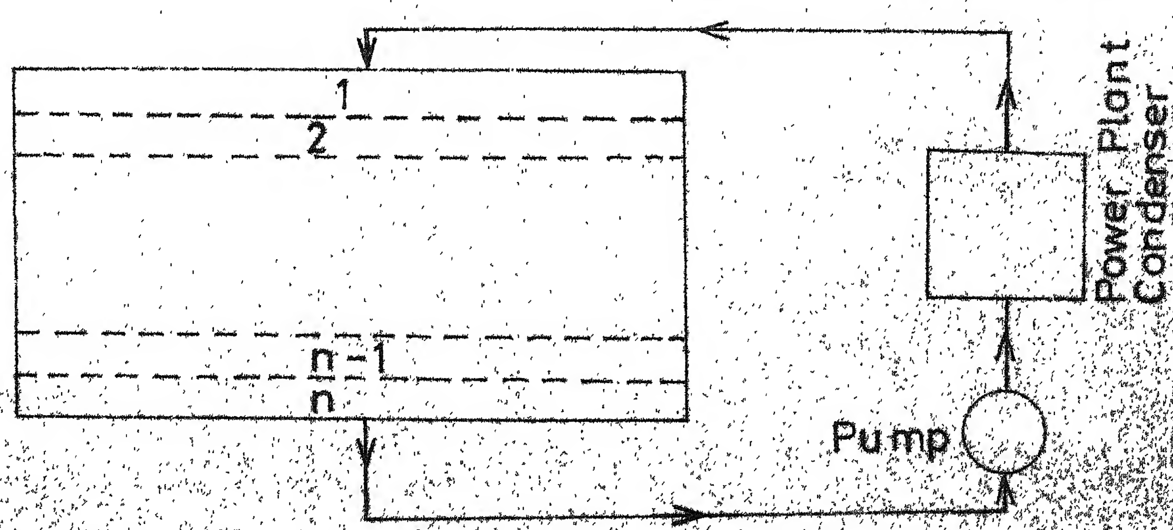

Fig. 1 (d) One dimensional approximation

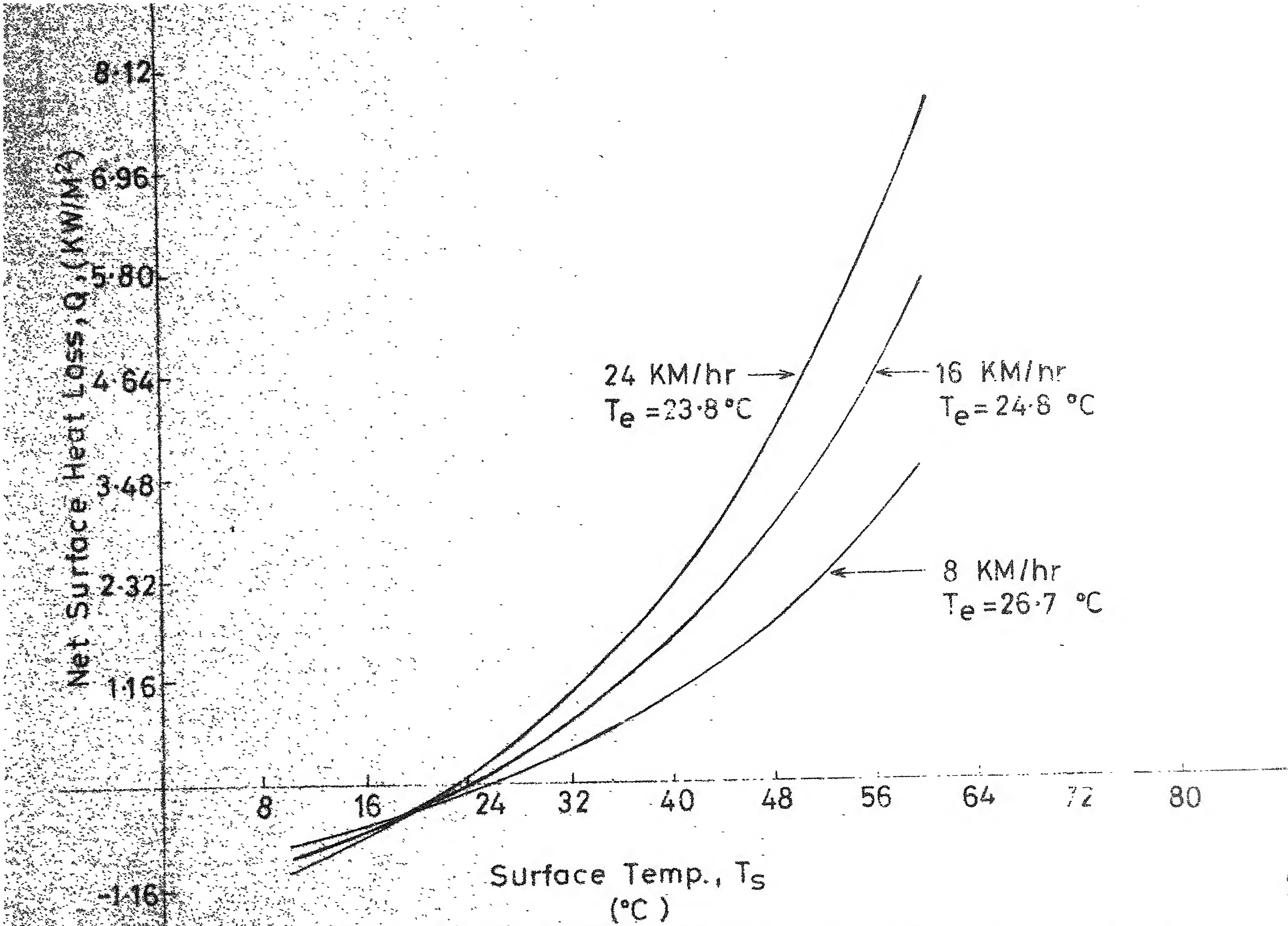

Fig. 2 Effect of surface temperature and wind velocity on surface heat loss

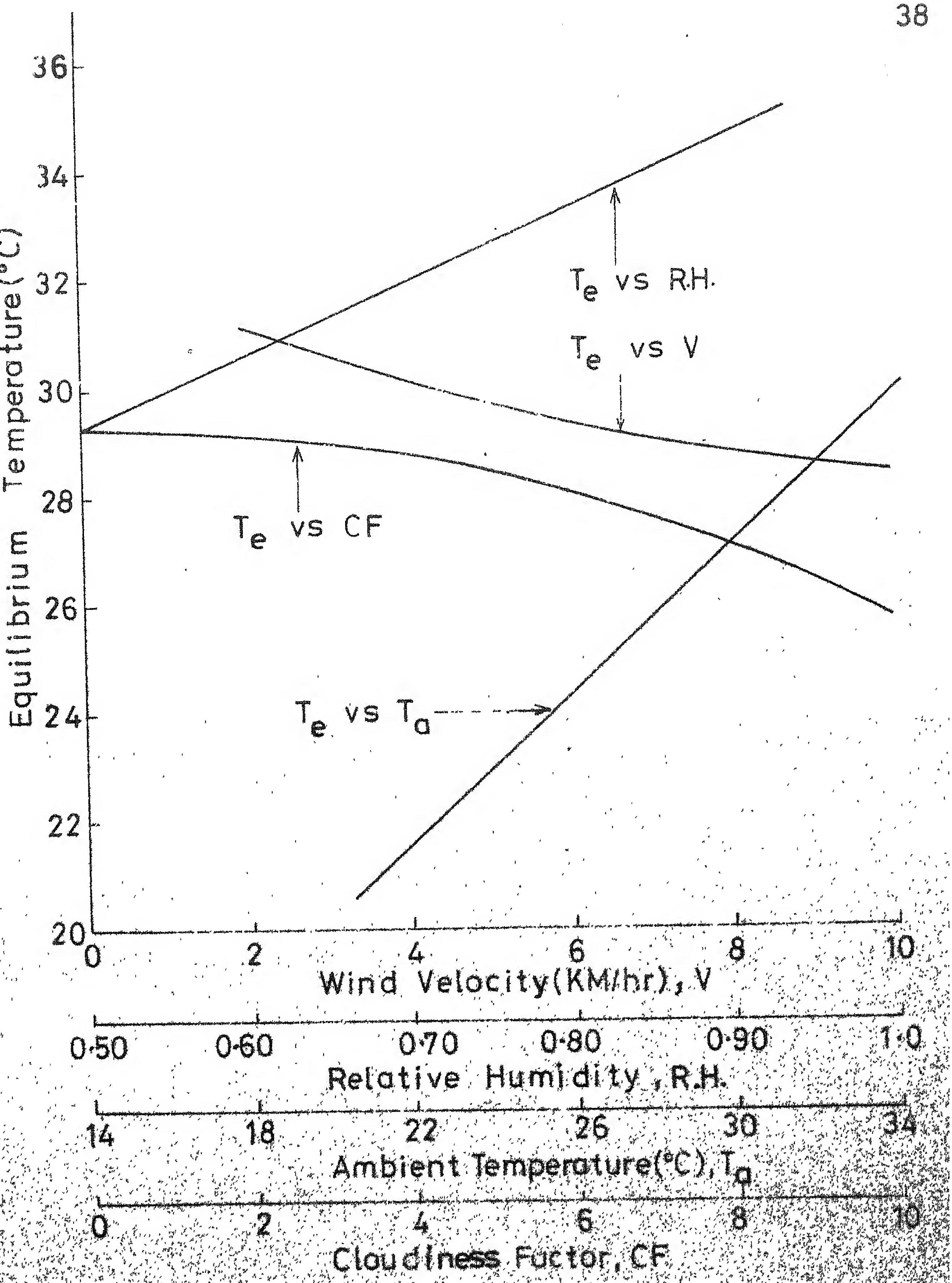

Fig. 3 Effect of meteorological parameters on equilibrium temperature

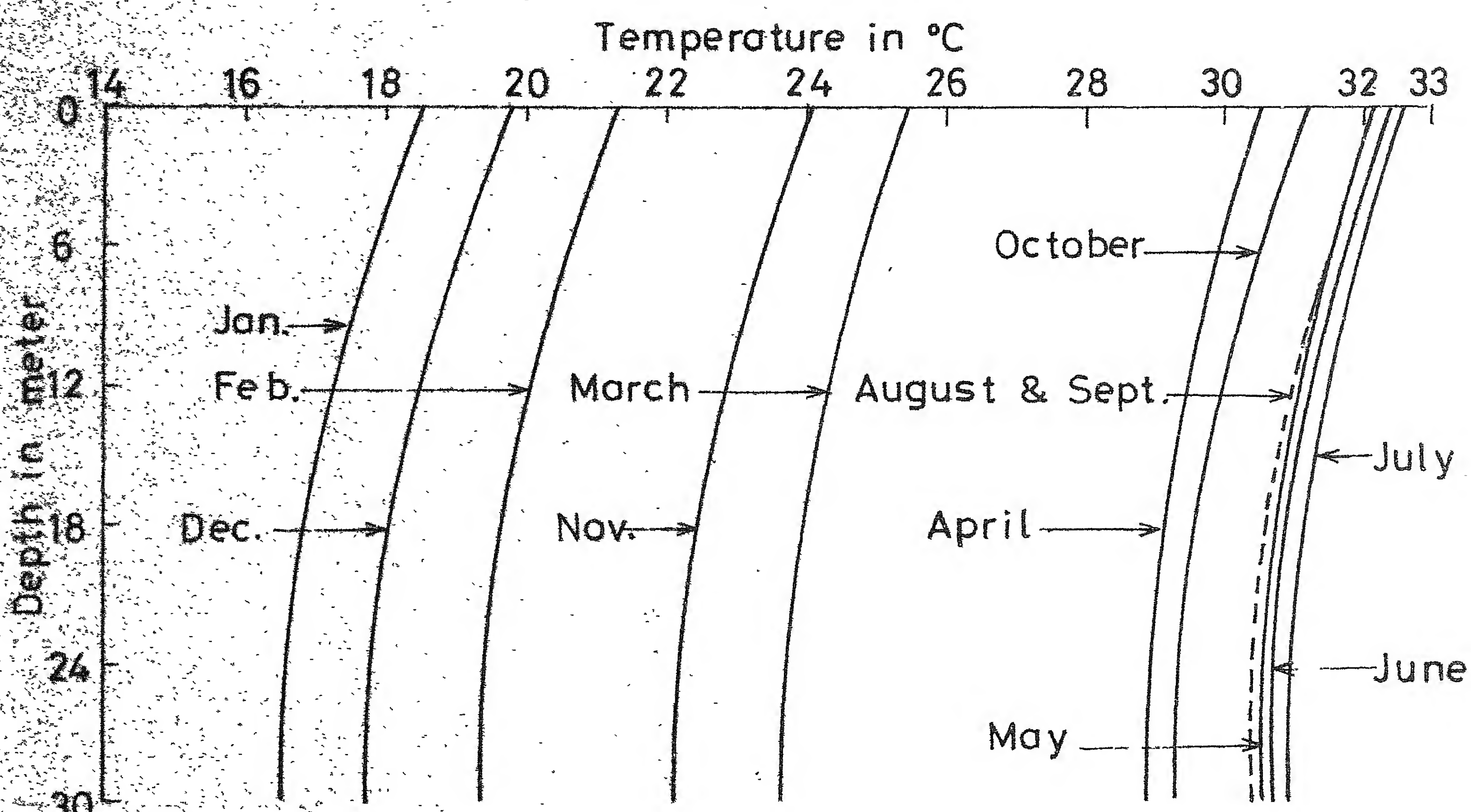

Fig 4 Monthly temperature distribution in cooling pond (Steady-state)

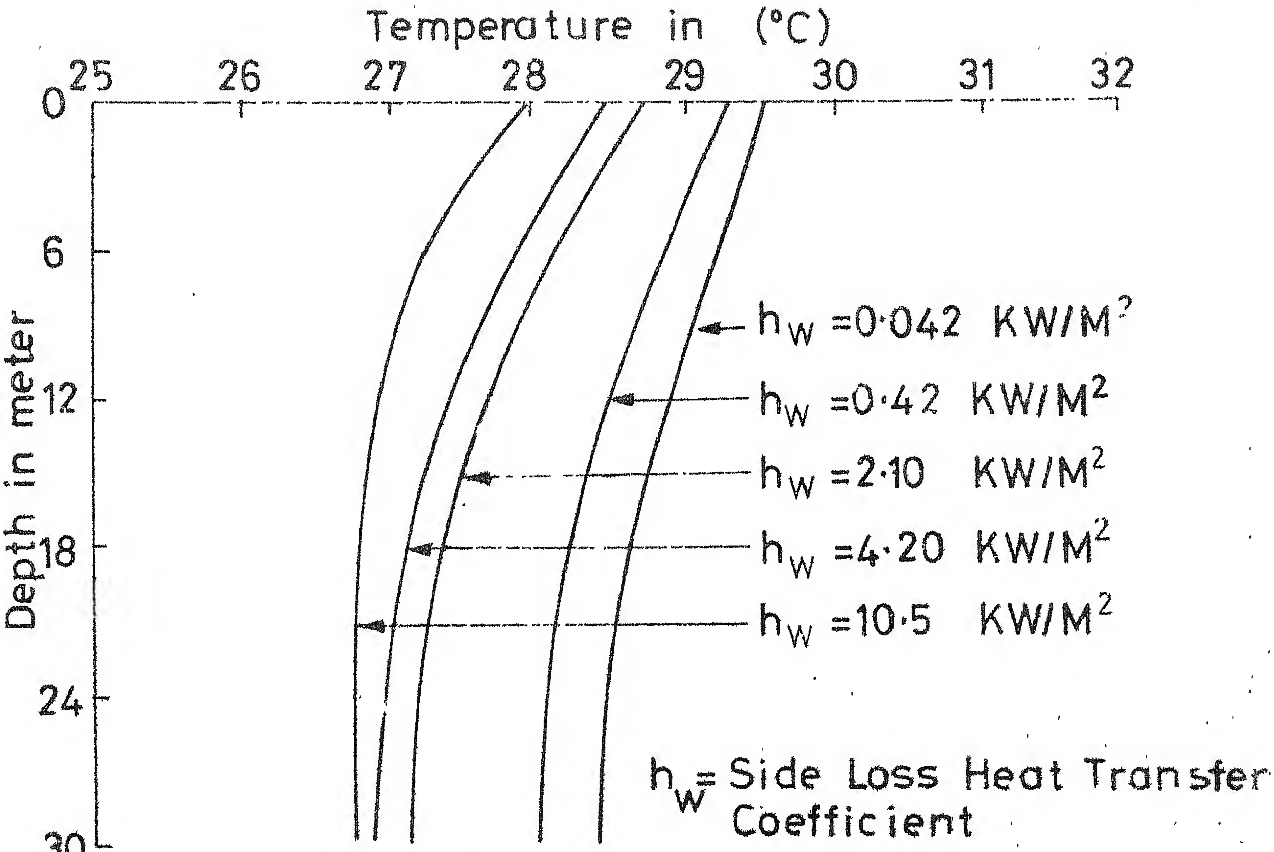

Fig. 5 Temperature profiles with side loss

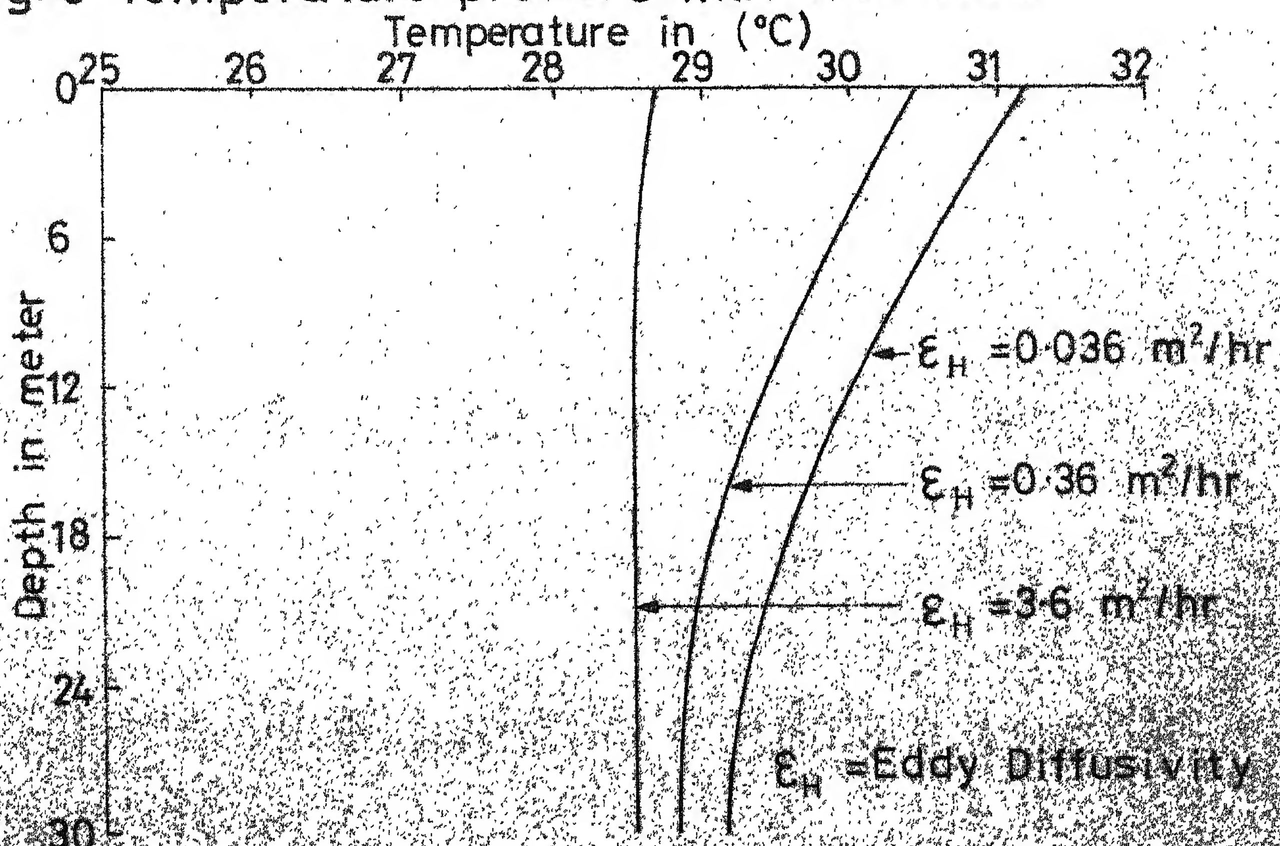

Fig.6 Effect of eddy diffusivity on steady-state temperature profiles

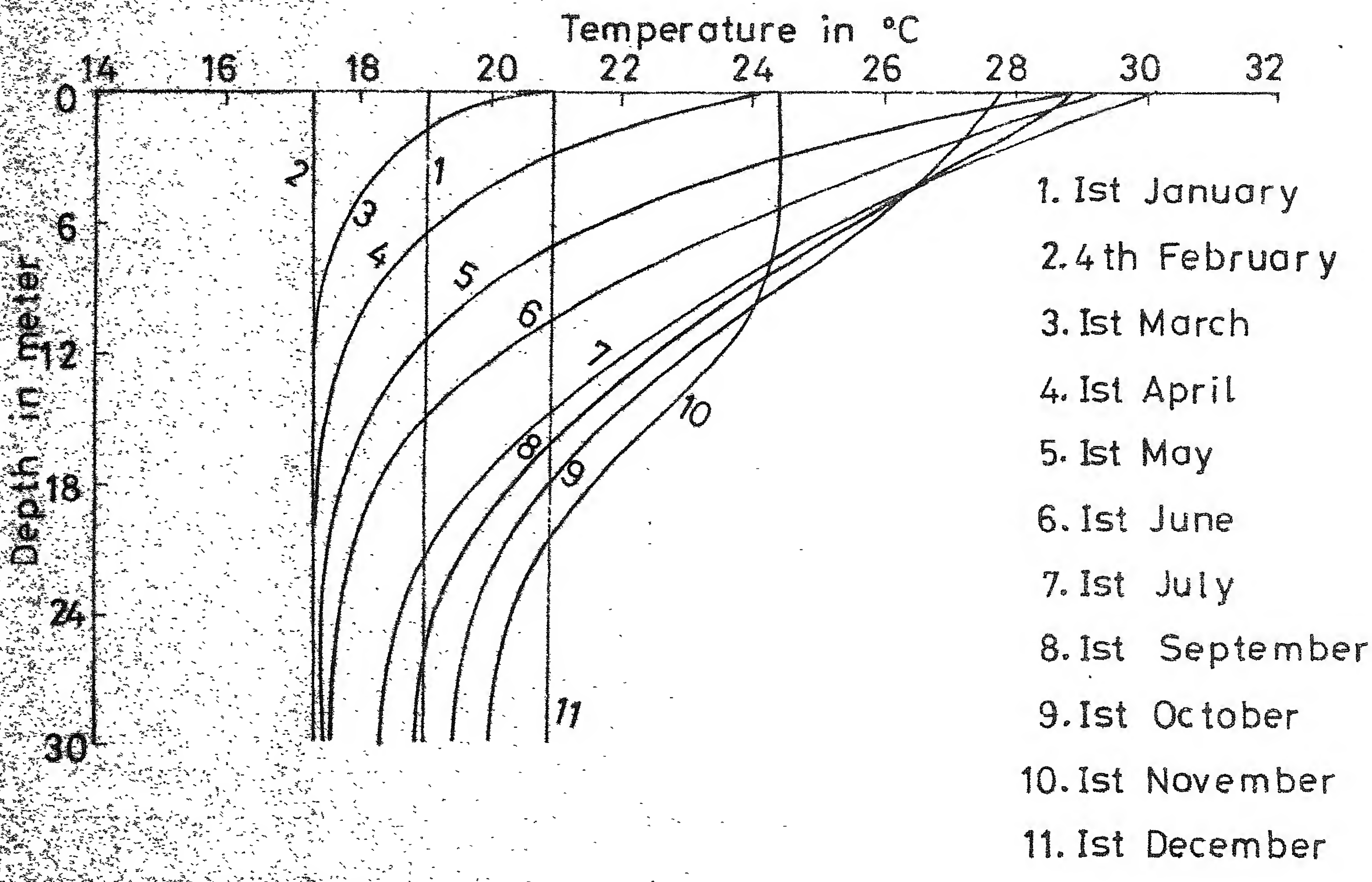

Fig. 7 Transient temperature distribution in cooling pond (With-out power plant)

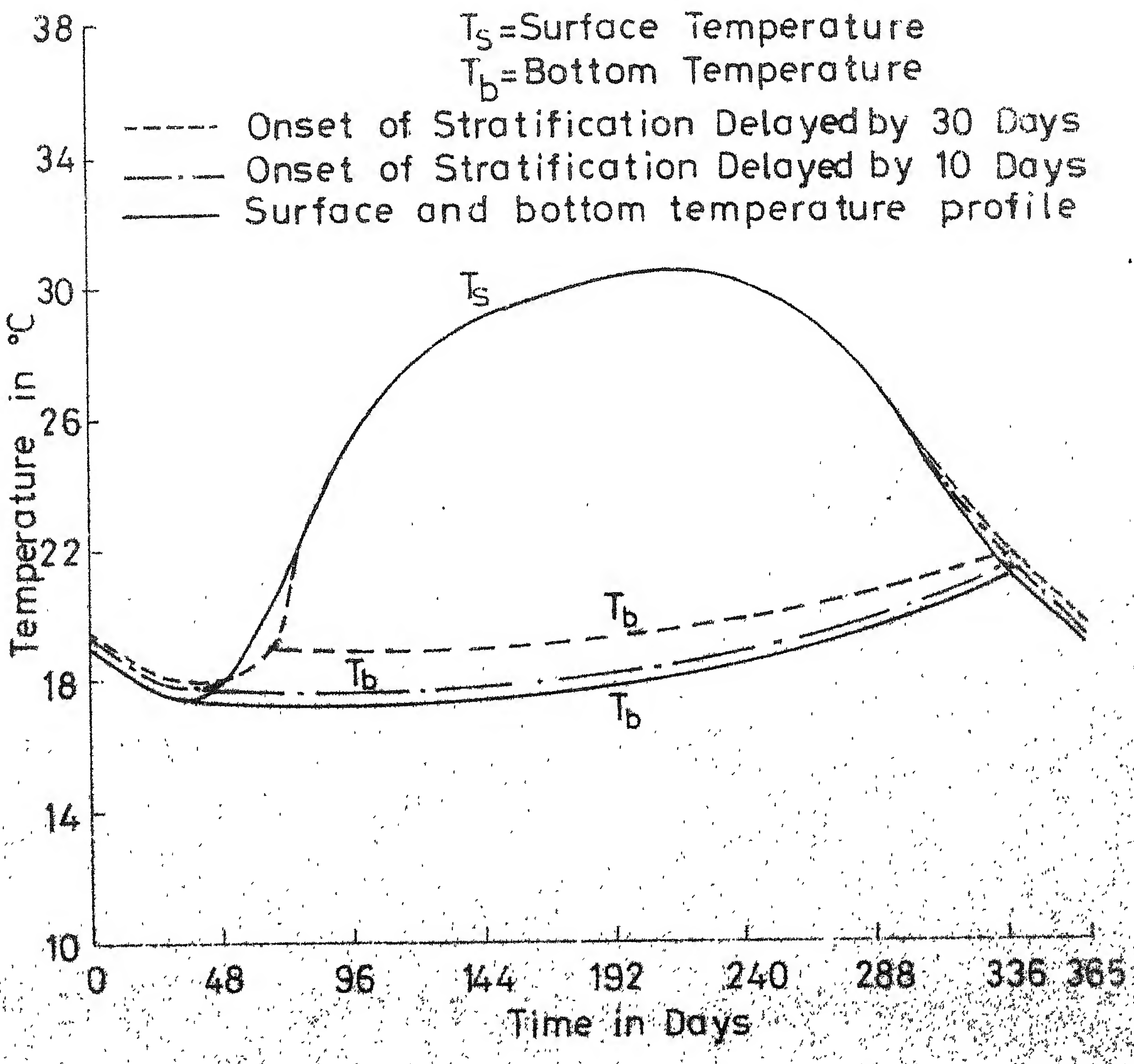

Fig-8 Effect of a delay in the onset of stratification of cooling pond on surface and bottom temperature profiles

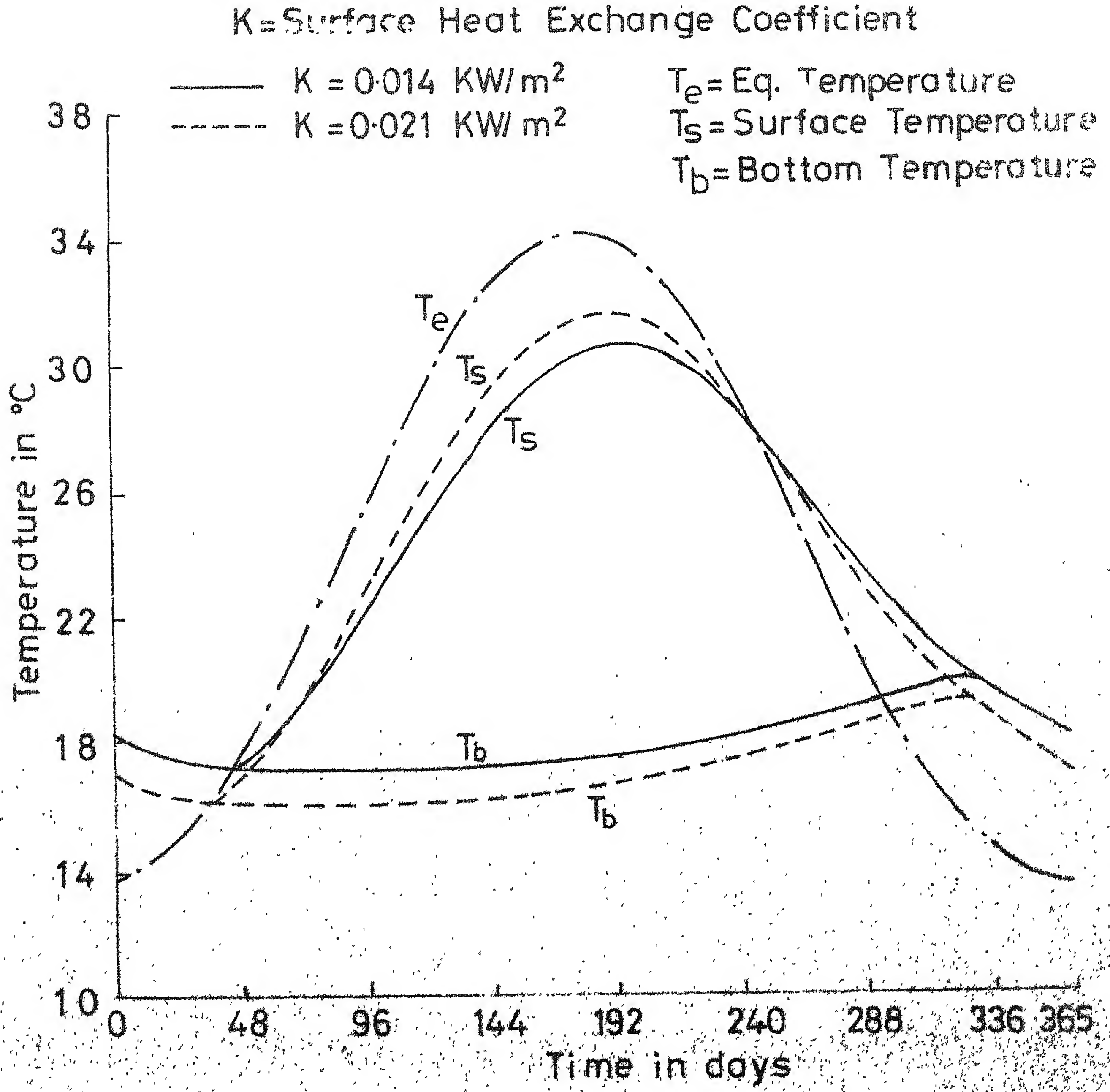

Fig. 9 Transient surface and bottom temperature profiles for cooling-pond (with-out power plant) considering periodic variations of equilibrium temperature

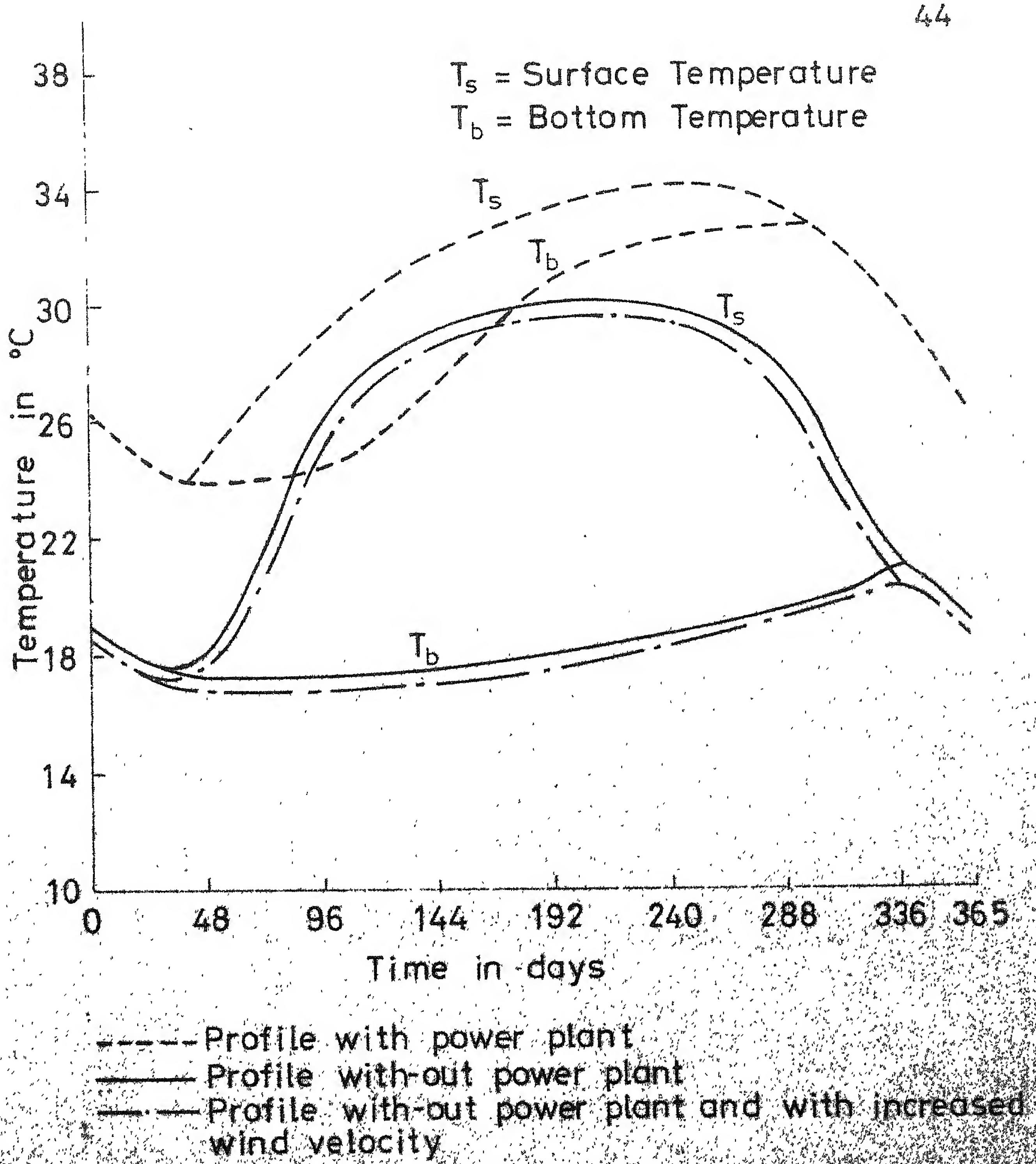

Fig.10 Transient surface and bottom temperature profiles for cooling-pond

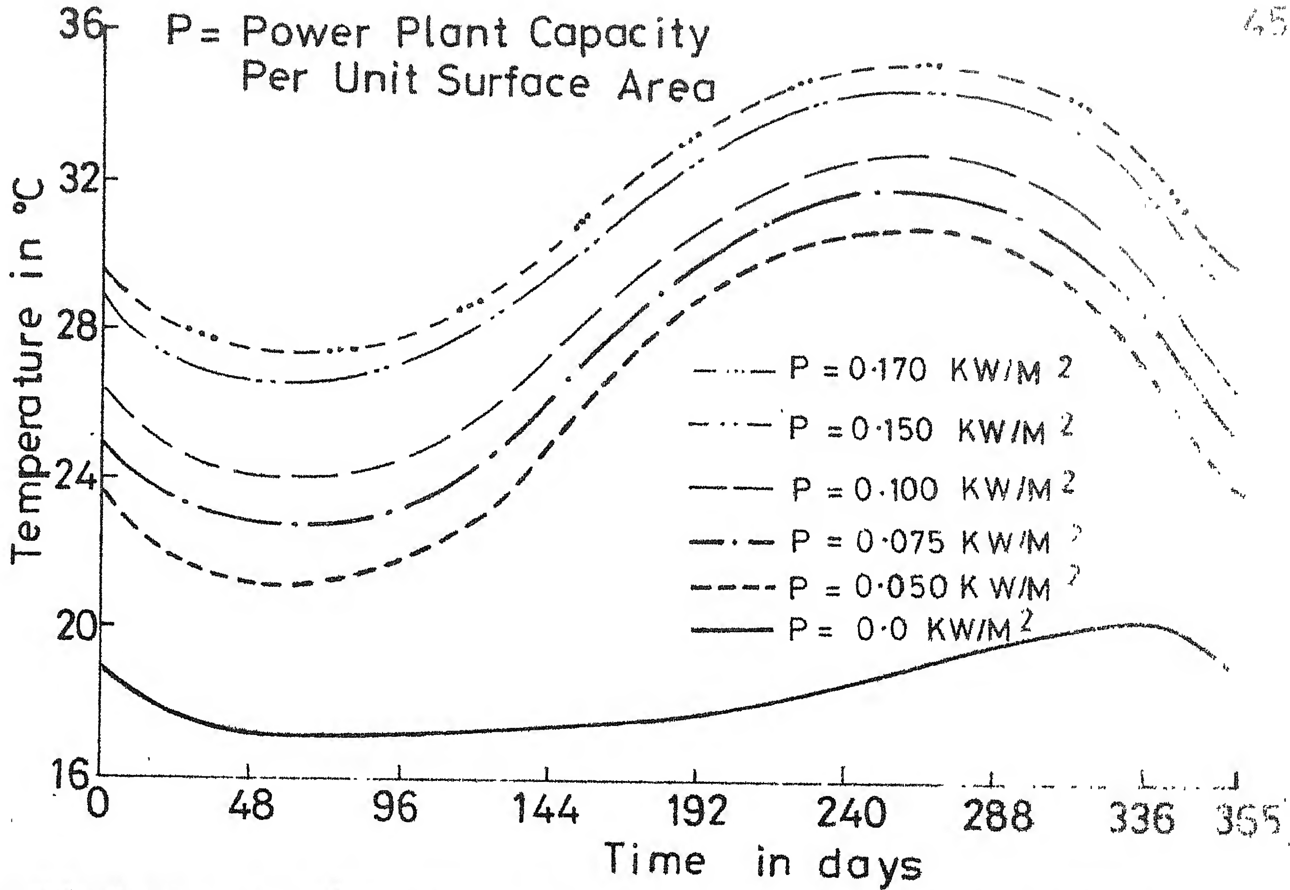

Fig.11 Effect of power plant capacity on intake temperature

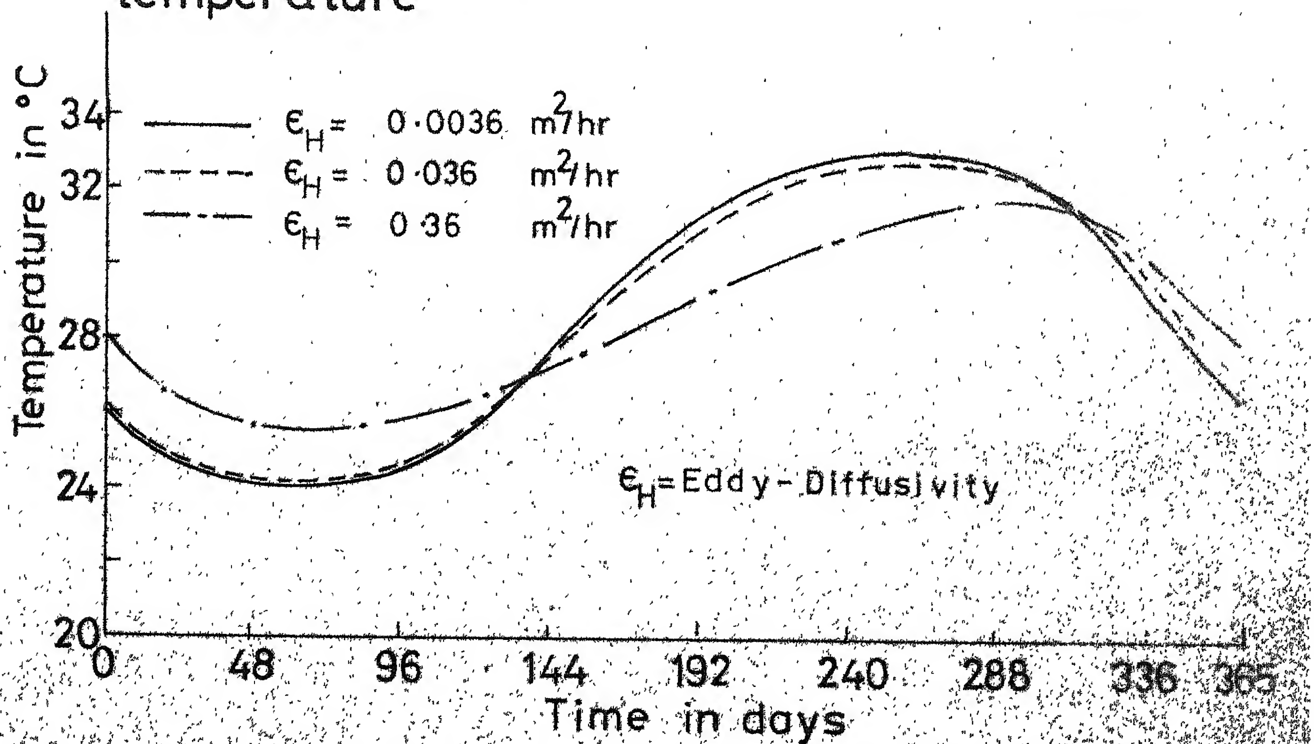

Fig. 12 Effect of eddy diffusivity on intake temperature

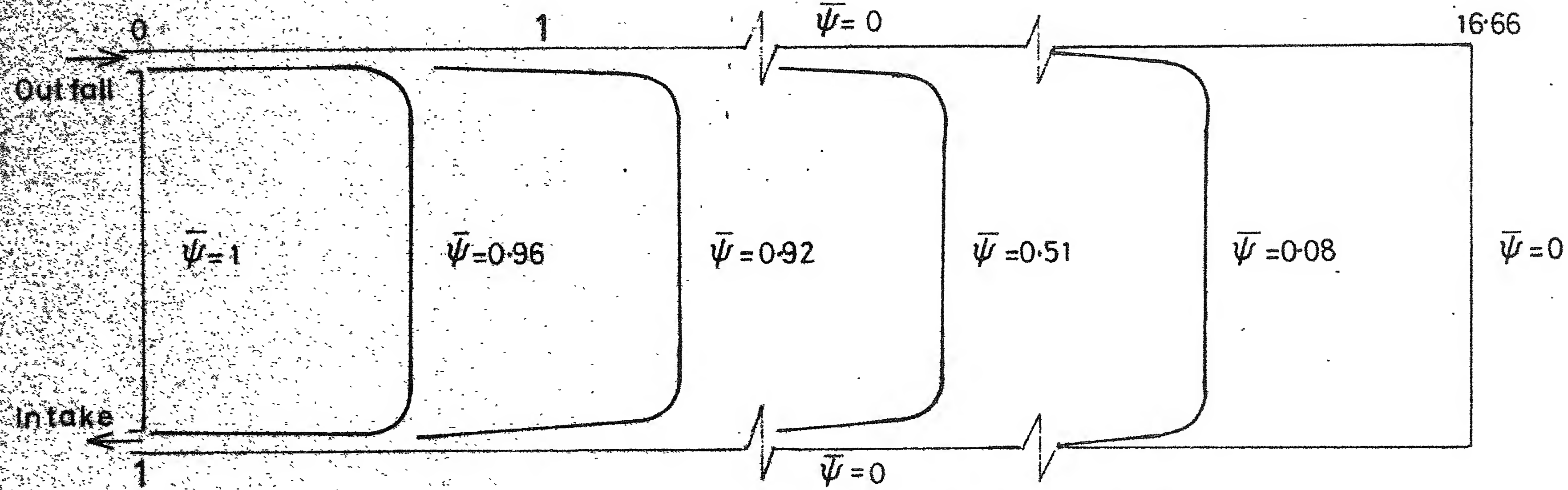

Fig. 13 Flow pattern in two dimensional inviscid flow

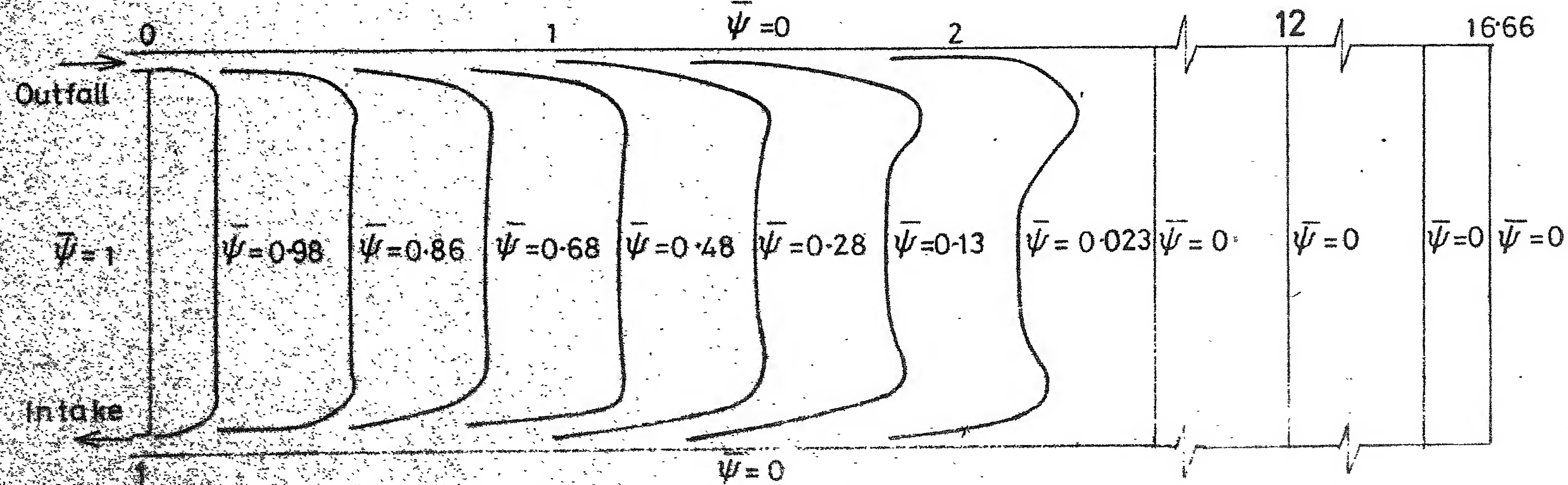

Fig. 14 Flow pattern in two dimensional creeping flow

APPENDIX I

FINITE DIFFERENCE EQUATIONS

The finite difference equations for one and two dimensional models are developed as given below:

<u>One Dimensional Model:</u>

The equations are developed for surface, bottom and intermediate elements separately, with the following parameters,

$$\epsilon_H = \frac{k}{\rho C_p} \qquad \text{(I.1)}$$

$$B = \frac{\epsilon_H}{\Delta z} \qquad \text{(I.2)}$$

$$C = \frac{h_w \cdot \Delta z}{\rho C_p L} \qquad \text{(I.3)}$$

$$D = \frac{1}{\rho C_p} \qquad \text{(I.4)}$$

Now the Eqn. (2.9) is represented, in finite difference form, as :

a) Surface element.

$$T_s = T(1) = \frac{w\,(T(n) + \Delta T) + B\,.\,T(2) + C.T_e - Q.D}{w + B + C} \quad \ldots. \qquad \text{(I.5)}$$

b) Intermediate elements.

$$T(I) = \frac{(w + B)\,.\,T(I-1) + B.T(I+1) + C.T_e}{w + 2.B + C} \quad \ldots. \qquad \text{(I.6)}$$

c) Bottom element.

$$T_b = T\ (n) = \frac{(w + B).T\ (n - 1) + C.\ T_e}{w + B + C} \qquad (I.7)$$

Eqn. (2.10) is represented as :

a) Surface element.

$$T_s = T\ (1) = \frac{B\ .\ T\ (2) + C\ .\ T\ (1) - D\ .\ Q}{B + C} \qquad (I.8)$$

b) Intermediate elements.

$$T\ (I) = \frac{B\ .\ T\ (I - 1) + B\ .\ T\ (I + 1) + C\ .\ T\ (I)}{2\ .\ B + C} \qquad (I.9)$$

c) Bottom element.

$$T_b = T\ (n) = \frac{B\ .\ T\ (n - 1) + C\ .\ T}{B + C}\ (n) \qquad (I.10)$$

and Eqn. (2.11) is represented as:

a) Surface element.

$$T_s = T\ (1) = \frac{w\ (\ T\ (n) + \Delta T) + B\ .\ T\ (2) + C\ .\ T\ (1) - Q.D}{w + B + C} \quad \ldots \quad (I.11)$$

b) Intermediate elements.

$$T\ (I) = \frac{(w + B)\ .\ T\ (I - 1) + B.T\ (I + 1) + C.T\ (I)}{w + 2.B + C} \quad \ldots \quad (I.12)$$

c) Bottom element.

$$T_b = T\ (n) = \frac{(w + B)\ .\ T\ (n - 1) + C\ .\ T\ (n)}{w + B + C} \quad \ldots \quad (I.13)$$

Two Dimensional Recirculation Model:

The following non-dimensional parameters are used,

$$\bar{\Psi}_{i,j} = \frac{\Psi_{i,j}}{U \, . \, d} \tag{I.14}$$

$$\bar{x} = \frac{x}{H} \quad , \quad \bar{z} = \frac{z}{H} \tag{I.15}$$

Now the Eqn. (2.22) is represented as ,

$$\bar{\Psi}_{i,j} = \frac{(\bar{\Psi}_{i+1,j} + \bar{\Psi}_{i+1,j} + C_1 \, . \, \bar{\Psi}_{i,j+1} + C_1 \, . \, \bar{\Psi}_{i,j-1})}{(2 + 2 \, . \, C_1)} \quad \ldots \tag{I.16}$$

where $C_1 = (L/H)^2$ (I.17)

and Eqn. (2.23) is represented as,

$$\Psi_{i,j} = \frac{(BB.AA - DC \, . \, AB - 2. \, C_1 \, . \, DB \, . \, AC + BC \, . \, AD - CC.DA.AE)}{BD} \quad \ldots \tag{I.18}$$

where, $AA = \bar{\Psi}_{i+1,j} + \bar{\Psi}_{i-1,j}$

$AB = \bar{\Psi}_{i+2,j} + \bar{\Psi}_{i-2,j}$

$AC = \bar{\Psi}_{i+1,j+1} + \bar{\Psi}_{i+1,j-1} + \bar{\Psi}_{i-1,j+1} + \bar{\Psi}_{i-1,j-1}$

$AD = \bar{\Psi}_{i,j+1} + \bar{\Psi}_{i,j-1}$

$AE = \bar{\Psi}_{i,j+2} + \bar{\Psi}_{i,j-2}$

$C_1 = (L/H)^2$

$CC = (L/H)^4$

$\bar{x} = (L/H) . \Delta \bar{x}_n$

$$DA = (\Delta \bar{x}_n)^4$$

$$DB = (\Delta \bar{x}_n \cdot \Delta \bar{z})^2$$

$$DC = (\Delta \bar{z})^4$$

$$BB = 4 \cdot DC + 4 \cdot C_1 \cdot DB$$

$$BC = 4 \cdot DB \cdot C_1 + 4 \cdot CC \cdot DA$$

$$BD = 6 \cdot DC + 8 \cdot C_1 \cdot DB + 6 \cdot CC \cdot DA \qquad \ldots \qquad (I.19)$$

APPENDIX II

INPUT DATA FOR THE NUMERICAL EXAMPLE

```
*****************************************************
[illegible] OF COLLECTOR PLATE A=1.[illegible]
[illegible] AT [illegible] H=[illegible]
[illegible]
[illegible] PLATE=[illegible] /
[illegible] C
[illegible] TEMPERATURE IN C
[illegible] HUMIDITY
[illegible] VELOCITY IN KM/HOUR
[illegible] TEMPERATURE OF SKY
[illegible] OPERATION CYCLE
[illegible] IN KCAL/DAY.M
[illegible] VAPOUR PRESSURE IN MM OF HG
*****************************************************
```

METEOROLOGICAL DATA AT [illegible]

[illegible] LATITUDE

PERIOD OF DATA JUNE 1974 TO MAY [illegible]

J A N U A R Y

A	V	CR	BETA	Q	ETA
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	477.	[illegible]

JULY

SEPTEMBER

OCTOBER

```
C                               APPENDIX III
C
C
C------------------------------------------------------------------------------
C
C     DETERMINATION OF ONE DIMENSIONAL VERTICAL TEMPERATURE DISTRIBUTION
C     IN COOLING POND
C
C------------------------------------------------------------------------------
C
C     THE INTAKE AND OUTFALL ARE CONSIDERED IN SAME VERTICAL PLANE
C     THE INTAKE IS TAKEN AT THE BOTTOM OF THE COOLING POND WHILE THE
C     OUTFALLIS TAKEN AT THE TOP SURFACE
C     A NATURAL LAKE IS A COOLING POND WITHOUT POWER PLANT
C     TOSUL IS SUBROUTINE TO DETERMINE TOTAL SURFACE HEAT LOSS FROM
C     COOLING POND
C     VIBHA IS SUBROUTINE TO DETERMINE SURFACE EQUILIBRIUM TEMPERATURE
C     DELZ IS DEPTH OF ELEMENT CONSIDERED IN VERTICAL DOWNWARD DIRECTION
C     DELTIM IS TIME STEP SIZE TAKEN AS ONE DAY
C     TE IS AVERAGE SURFACE EQUILIBRIUM TEMPERATURE
C     AMUH IS EDDY THERMAL DIFFUSIVITY
C     BETA IS ATMOSPHERIC RADIATION FACTOR
C     CF IS CLOUDINESS FACTOR
C     V IS WIND VELOCITY ALONG WATER SURFACE
C     QTS IS TOTAL SURFACE HEAT LOSS
C     QSE IS NET SOLAR RADIATION ON EARTH SURFACE AT KANPUR
C
C------------------------------------------------------------------------------
C
C                          STEADY STATE SOLUTION
C
C------------------------------------------------------------------------------
C
C******************************************************************************
C     MONTHLY TEMPERATURE DISTRIBUTION IS COMPUTED
C     COOLING POND WITH POWER PLANT IS CONSIDERED
C******************************************************************************
$IBJOB
$IBFTC MAIN
      DIMENSION ATA(12),ARH(12),AV(12),ACF(12),ABETA(12),AQSE(12)
      DIMENSION AESTA(12)
      DIMENSION T(125),TOLD(125)
      COMMON ATA,ARH,AV,ACF,ABETA,AQSE,AESTA
      READ 71,(ATA(II),ARH(II),AV(II),ACF(II),ABETA(II),AQSE(II),AESTA(I
     1I),II=1,12)
      N=20
      N1=N-1
      RO=1000.
      DELZ=1.5
      HW=1800.0
      CP=1.
      W=0.022
      CL=1000.
      D=1./(RO*CP)
      DO 222 II=1,12
      TA=ATA(II)
      CALL VIBHA(TE,II)
      AT=TE
      TB=TE
      FOX=TE
      DOX=TE
      DELT=9.
       B=AMUH/DELZ
      C=(HW*DELZ)/(RO*CP*CL)
      X2=W+B
      X3=W+2.*B+C
      X=W+B+C
      ITR=0
   10 ITR=ITR+1
      IF(ITR.GT.1)FOX=T(2)
      CALL TOSUL(QTS,AT,QBR,QS,QH,QE,II)
      IF(ITR.EQ.1) GO TO 101
      DO 90 I=1,N
90    TOLD(I)=T(I)
101   T(1)=(W*(TB+DELT)+B*FOX+C*TE-D*QTS)/X
      AT=T(1)
      DO 20 I=2,N1
      IF(ITR.GT.1)DOX=T(I+1)
20    T(I)=(X2*T(I-1)+B*DOX+C*TE)/X3
      TB=(X2*T(N-1)+C*TE)/X
      T(N)=TB
      IF(ITR.EQ.1) GO TO 10
```

```
      BIG=0.0
      DO 80 I=1,N
      DIFF=ABS(T(I)-TOLD(I))
      IF(BIG.LE.DIFF)BIG=DIFF
80    CONTINUE
      IF(BIG.LE.0.01) GO TO 40
      IF(ITR.EQ.500) GO TO 40
      GO TO 10
   40 PRINT 50,ITR
      PRINT 39,TE
53    FORMAT(5F9.5)
39    FORMAT(2X,*TE=*,F6.2)
  50   FORMAT(2X,*ITR=*,I3)
99    PRINT 60,(T(I),I=1,N1),TB
60    FORMAT(1H ,10X,5F15.5)
70    FORMAT(1H ,I4,10E11.4)
71    FORMAT(7F9.3)
      STOP
      END
C
$IBFTC TOSUL
      SUBROUTINE TOSUL(QTS,T1,QBR,QS,QH,QE,II)
      DIMENSION ATA(12),ARH(12),AV(12),ACF(12),ABETA(12),AQSE(12)
      DIMENSION AESTA(12)
      DIMENSION TT(51),ESTT(51),POL(55)
      COMMON ATA,ARH,AV,ACF,ABETA,AQSE,AESTA
      TA=ATA(II)
      ESTA=AESTA(II)
      QSE=AQSE(II)
      BETA=ABETA(II)
      CF=ACF(II)
      V=AV(II)
      RH=ARH(II)
      TT(1)=10.
       DO 10 I=2,51
   10  TT(I)=TT(I-1)+1.
      DATA ESTT/9.204,9.839,10.512,11.225,11.982,12.781,13.628,14.524,15
     1.47,16.47,17.53,18.64,19.82,21.06,22.37,23.75,25.20,26.73,28.34,30
     2.03,31.81,33.69,35.65,37.72,39.89,42.17,44.55,47.06,49.69,52.44,55
     3.31,58.33,61.49,64.80,68.25,71.87,75.64,79.59,83.72,88.02,92.52,97
     4.54,102.10,107.21,112.53,118.06,123.83,129.85,136.11,142.62,149.4/
       DO 20 I=1,51
       IF(T1.GT.TT(I)) GO TO 20
      IWNT=I
       GO TO 30
   20  CONTINUE
   30  IF(IWNT.EQ.1) GO TO 91
       J1=IWNT-1
       J2=IWNT+1
       GO TO 92
   91  J1=IWNT
       J2=IWNT+2
    92 DO 40 J=J1,J2
      POL(J)=1.
      DO 40 I=J1,J2
       IF(I-J)50,40,50
   50  POL(J)=(POL(J)*(T1-TT(I)))/(TT(J)-TT(I))
   40   CONTINUE
       EST1=0.0
        DO 60 I=J1,J2
   60  EST1=EST1+POL(I)*ESTT(I)
       QBR=4.74E-08*((273.+T1)**4-BETA*(273.+TA)**4)
       QS=-(1.-0.0071*(CF**2))*QSE
      QE=19.4*(0.48+0.0755*V)*(EST1-RH*ESTA)
      QH=9.7*(0.48+0.0755*V)*(T1-TA)
       QTS=QBR+QS+QH+QE
        RETURN
        END
C
$IBFTC VIBHA
       SUBROUTINE VIBHA(TE,II)
       DIMENSION ATA(12),ARH(12),AV(12),ACF(12),ABETA(12),AQSE(12)
       DIMENSION AESTA(12)
       DIMENSION TS(51),ESTS(51)
       DIMENSION TEW(365),POL(51)
       DIMENSION TP(51),QTSP(51),TR(51),QTSR(51)
       COMMON ATA,ARH,AV,ACF,ABETA,AQSE,AESTA
       TA=ATA(II)
       RH=ARH(II)
       V=AV(II)
       CF=ACF(II)
       BETA=ABETA(II)
```

```
      QSE=AQSE(II)
      ESTA=AESTA(II)
      TS(1)=10.
      DO 25 I=2,51
25    TS(I)=TS(I-1)+1.
      DATA ESTS/9.204,9.839,10.512,11.225,11.982,12.781,13.628,14.524,15
     1.47,16.47,17.53,18.64,19.82,21.06,22.37,23.75,25.20,26.73,28.34,30
     2.03,31.81,33.69,35.65,37.72,39.89,42.17,44.55,47.06,49.69,52.44,55
     3.31,58.33,61.49,64.88,68.25,71.87,75.64,79.59,83.72,88.02,92.52,97
     4.54,102.10,107.21,112.53,118.06,123.83,129.85,136.11,142.62,149.4/
      DO 33 I=1,51
      T1=TS(I)
      EST1=ESTS(I)
       QBR=4.74E-08*((273.+T1)**4-BETA*(273.+TA)**4)
       QS=-(1.-0.0071*(CF**2))*QSE
      QH=9.7*(0.48+0.0755*V)*(T1-TA)
      QE=19.4*(0.48+0.0755*V)*(EST1-RH*ESTA)
       QTS=QBR+QS+QH+QE
      TR(I)=T1
      QTSR(I)=QTS
33    CONTINUE
      DO 100 I=1,51
      IF(QTSR(I).LT.0.0) GO TO 100
      IWNT=I
      GO TO 101
100   CONTINUE
101   J1=IWNT-2
      J2=IWNT
      DO 102 I=J1,J2
      POL(I)=1.0
      DO 102 J=J1,J2
      IF(I-J) 103,102,103
 103  POL(I)=POL(I)*(-QTSR(J))/(QTSR(I)-QTSR(J))
102     CONTINUE
      TE=0.0
      DO 104 K=J1,J2
104   TE=TE+POL(K)*TR(K)
      RETURN
      END
$ENTRY
C
C-----------------------------------------------------------------------------
C
C                           TRANSIENT SOLUTION
C
C-----------------------------------------------------------------------------
C
C  ***********************************************************************
C       ONLY NATURAL LAKE IS CONSIDERED
C  ***********************************************************************
$IBJOB
$IBFTC MAIN
      DIMENSION ATA(365),ARH(365),AV(365),ACF(365),ABETA(365),AQSE(365)
      DIMENSION AESTA(365),TFRST(15),T(15)
      COMMON ATA,ARH,AV,ACF,ABETA,AQSE,AESTA
      READ 100,(ATA(I),ARH(I),AV(I),ACF(I),ABETA(I),AQSE(I),AESTA(I),I=1
     1,365)
      TE=15.8
      DELZ=2.0
      CODE=1.0
      DELTIM=24.0
      RO=1000.0
      ITR=0
      CP=1.00
      AMUH=0.036
      B=AMUH/DELZ
      C=DELZ/DELTIM
      X1=B+C
      X2=2.*B+C
      X3=1./(RO*CP)
      JC=1
      N=15
      N1=N-1
      DO 1 I=1,15
      TFRST(I)=TE
      T(I)=TE
1     CONTINUE
      AT=T(1)
      TB=T(N)
98    DO 2 J=JC,365
      CALL TOSUL(QTS,AT,J)
      T(1)=(B*T(2)+C*T(1)-QTS*X3)/X1
```

```
      AT=T(1)
      TAVRG=T(1)
      DO 3 I=2,N1
3     T(I)=(B*T(I-1)+B*T(I+1)+C*T(I))/X2
      TB=(B*T(N1)+C*T(N))/X1
      T(N)=TB
      JK=1
      DO 4 I=2,N
      IF(T(1)-T(I))6,6,4
6     JK=I
        TAVRG=TAVRG+T(JK)
4     CONTINUE
      IF(JK.EQ.1) GO TO 97
      T(1)=TAVRG/FLOAT(JK)
      DO 7 I=2,JK
      T(I)=T(1)
7     CONTINUE
71     AT=T(1)
      IF(CODE.LT.9.0) GO TO 80
      PRINT 101,J,(T(I),I=1,N)
80    IF(J.NE.1) GO TO 2
      ITR=ITR+1
      BIG=0.0
      DO 10 I=1,N
      CHECK=ABS(T(I)-TFRST(I))
      IF(BIG.LT.CHECK) BIG=CHECK
10    CONTINUE
      IF(BIG.LT.0.0001) GO TO 99
      DO 5 I=1,N
5     TFRST(I)=T(I)
2     CONTINUE
      IF(CODE.EQ.1.) GO TO 98
      IF(CODE.GT.2.0) GO TO 77
99    CODE=10.0
      PRINT 101,J,(T(I),I=1,N)
      JC=2
      GO TO 98
102   FORMAT(1H ,7F9.3)
100   FORMAT(7F9.3)
101   FORMAT(1H ,I3,15F7.3)
77    PRINT 41,ITR
 41   FORMAT(1X,*ITR=*,I5)
      STOP
      END
C
$IBFTC TOSUL
      SUBROUTINE TOSUL(QTS,T1,II)
      DIMENSION TT(51),ESTT(51),POL(55)
      DIMENSION AESTA(365),TFRST(15),T(15)
      DIMENSION ATA(365),ARH(365),AV(365),ACF(365),ABETA(365),AQSE(365)
      COMMON ATA,ARH,AV,ACF,ABETA,AQSE,AESTA
      RH=ARH(II)
      TA=ATA(II)
      V=AV(II)
      CF=ACF(II)
      BETA=ABETA(II)
      QSE=AQSE(II)
      ESTA=AESTA(II)
      TT(1)=10.
       DO 10 I=2,51
10     TT(I)=TT(I-1)+1.
       DATA ESTT/9.204,9.839,10.512,11.225,11.982,12.781,13.628,14.524,15
     1.47,16.47,17.53,18.64,19.82,21.06,22.37,23.75,25.20,26.73,28.34,30
     2.03,31.81,33.69,35.65,37.72,39.89,42.17,44.55,47.06,49.69,52.44,55
     3.31,58.33,61.49,64.80,68.25,71.87,75.64,79.59,83.72,88.02,92.52,97
     4.54,102.10,107.21,112.53,118.06,123.83,129.85,136.11,142.62,149.4/
       DO 20 I=1,51
        IF(T1.GT.TT(I)) GO TO 20
       IWNT=I
       GO TO 30
20     CONTINUE
30     IF(IWNT.EQ.1) GO TO 91
       J1=IWNT-1
       J2=IWNT+1
       GO TO 92
91     J1=IWNT
       J2=IWNT+2
92     DO 40 J=J1,J2
      POL(J)=1.
       DO 40 I=J1,J2
        IF(I-J)50,40,50
50     POL(J)=(POL(J)*(T1-TT(I)))/(TT(J)-TT(I))
```

```
40      CONTINUE
       EST1=0.0
        DO 60 I=J1,J2
60     EST1=EST1+POL(I)*ESTT(I)
       QBR=4.74E-08*((273.+T1)**4-BETA*(273.+TA)**4)
       QS=-(1.-0.0071*(CF**2))*QSE/24.
      QH=9.7*(0.48+0.0755*V)*(T1-TA)
      QE=19.4*(0.48+0.0755*V)*(EST1-RH*ESTA)
       QTS=QBR+QS+QH+QE
        RETURN
        END
$ENTRY
C
C  ****************************************************************************
C       COOLING POND WITH POWER PLANT IS CONSIDERED
C  ****************************************************************************
$IBJOB
$IBFTC MAIN
      DIMENSION DELTT(10)
      DIMENSION AMUHH(10)
      DIMENSION ATA(365),ARH(365),AV(365),ACF(365),ABETA(365),AQSE(365)
      DIMENSION AESTA(365),TFRST(15),T(15)
      COMMON ATA,ARH,AV,ACF,ABETA,AQSE,AESTA
      READ 100,(ATA(I),ARH(I),AV(I),ACF(I),ABETA(I),AQSE(I),AESTA(I),I=1
     1,365)
      TE=15.8
      AMUH=0.036
      DELZ=2.0
      CODE=1.0
      DELTIM=24.0
      RO=1000.0
      ITR=0
      CP=1.00
      DELT=9.0
      W=0.011
      C=DELZ/DELTIM
      X3=1./(RO*CP)
      JC=1
      N=15
      N1=N-1
      B=AMUH/DELZ
      X1=W+B+C
      X2=W+2.*B+C
      DO 1 I=1,15
      TFRST(I)=TE
      T(I)=TE
1     CONTINUE
      AT=T(1)
      TB=T(N)
98    DO 2 J=JC,365
      CALL TOSUL(QTS,AT,J)
      T(1)=(W*(TB+DELT)+B*T(2)+C*T(1)-QTS*X3)/X1
      AT=T(1)
      TAVRG=T(1)
      DO 3 I=2,N1
3     T(I)=((W+B)*T(I-1)+B*T(I+1)+C*T(I))/X2
      TB=((W+B)*T(N1)+C*T(N))/X1
      T(N)=TB
      JK=1
      DO 4 I=2,N
      IF(T(1)-T(I))6,6,4
6     JK=I
      TAVRG=TAVRG+T(JK)
4     CONTINUE
      IF(JK.EQ.1) GO TO 97
      T(1)=TAVRG/FLOAT(JK)
      DO 7 I=2,JK
      T(I)=T(1)
7     CONTINUE
      AT=T(1)
97    IF(CODE.LT.9.0) GO TO 80
      PRINT 101,J,(T(I),I=1,N)
80    IF(J.NE.1) GO TO 2
      ITR=ITR+1
      BIG=0.0
      DO 10 I=1,N
      CHECK=ABS(T(I)-TFRST(I))
      IF(BIG.LT.CHECK) BIG=CHECK
10    CONTINUE
      IF(BIG.LT.0.0001) GO TO 99
      DO 5 I=1,N
5     TFRST(I)=T(I)
```

```
2       CONTINUE
        IF(CODE.EQ.1.) GO TO 98
        IF(CODE.GT.2.0) GO TO 77
99      CODE=10.0
        PRINT 101,J,(T(I),I=1,N)
        JC=2
        GO TO 98
102     FORMAT(1H ,7F9.3)
100     FORMAT(7F9.3)
59      FORMAT(3F7.4)
101     FORMAT(1H ,I3,15F7.3)
77      PRINT 41,ITR
 41     FORMAT(1X,*ITR=*,I5)
  591   CONTINUE
        STOP
        END
C
$IBFTC TOSUL
        SUBROUTINE TOSUL(QTS,T1,II)
        DIMENSION TT(51),ESTT(51),POL(55)
        DIMENSION AESTA(365),TFRST(15),T(15)
        DIMENSION ATA(365),ARH(365),AV(365),ACF(365),ABETA(365),AQSE(365)
        COMMON ATA,ARH,AV,ACF,ABETA,AQSE,AESTA
        TA=ATA(II)
         V=AV(II)
        ESTA=AESTA(II)
        QSE=AQSE(II)
        BETA=ABETA(II)
        CF=ACF(II)
        RH=ARH(II)
        TT(1)=10.
         DO 10 I=2,51
  10     TT(I)=TT(I-1)+1.
        DATA ESTT/9.204,9.839,10.512,11.225,11.982,12.781,13.628,14.524,15
      1.47,16.47,17.53,18.64,19.82,21.06,22.37,23.75,25.20,26.73,28.34,30
      2.03,31.81,33.69,35.65,37.72,39.89,42.17,44.55,47.06,49.69,52.44,55
      3.31,58.33,61.49,64.80,68.25,71.87,75.64,79.59,83.72,88.02,92.52,97
      4.54,102.10,107.21,112.53,118.06,123.83,129.85,136.11,142.62,149.4/
         DO 20 I=1,51
         IF(T1.GT.TT(I)) GO TO 20
        IWNT=I
         GO TO 30
  20     CONTINUE
  30     IF(IWNT.EQ.1) GO TO 91
         J1=IWNT-1
         J2=IWNT+1
         GO TO 92
  91     J1=IWNT
         J2=IWNT+2
   92    DO 40 J=J1,J2
        POL(J)=1.
        DO 40 I=J1,J2
         IF(I-J)50,40,50
  50     POL(J)=(POL(J)*(T1-TT(I)))/(TT(J)-TT(I))
  40      CONTINUE
         EST1=0.0
          DO 60 I=J1,J2
  60     EST1=EST1+POL(I)*ESTT(I)
         QBR=4.74E-08*((273.+T1)**4-BETA*(273.+TA)**4)
         QS=-(1.-0.0071*(CF**2))*QSE/24.
        QE=19.4*(0.48+0.0755*V)*(EST1-RH*ESTA)
        QH=9.7*(0.48+0.0755*V)*(T1-TA)
         QTS=QBR+QS+QH+QE
          RETURN
          END
$ENTRY
C
C------------------------------------------------------------------------
C
C                          PERIODIC SOLUTION
C
C------------------------------------------------------------------------
C
C  **********************************************************************
C       NATURAL LAKE WITH PERIODIC VARIATION OF EQUILIBRIUM TEMPERATURE
C       IS CONSIDERED
C  **********************************************************************
$IBJOB
$IBFTC MAIN
         DIMENSION TEAS(365)
         DIMENSION AESTA(365),TFRST(15),T(15)
         DIMENSION ATA(365),ARH(365),AV(365),ACF(365),ABETA(365),AQSE(365)
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      COMMON ATA,ARH,AV,ACF,ABETA,AQSE,AESTA
      DIMENSION QTSS(365)
       DIMENSION TEW(365)
      READ 100,(ATA(I),ARH(I),AV(I),ACF(I),ABETA(I),AQSR(I),AESTA(I),I=1
     1,365)
      TEP=15.8
      DELZ=2.0
      CODE=1.0
      DELTIM=24.0
      RO=1000.0
      ITR=0
      CP=1.00
      AMUH=0.036
      B=AMUH/DELZ
      C=DELZ/DELTIM
      X1=B+C
      X2=2.*B+C
      X3=1./(RO*CP)
      JC=1
      N=15
      N1=N-1
      DO 1 I=1,15
      TFRST(I)=TEP
      T(I)=TEP
1     CONTINUE
      AT=T(1)
      TB=T(N)
      DO 51 J=1,365
       CALL VIBHA(TES,J)
      TEW(J)=TES
51    CONTINUE
      PRINT 83,(TEW(J),J=1,365,2)
83    FORMAT(1X,16F7.2)
      TEMAX=TEW(1)
      DO 58 I=2,365
      IF(TEMAX.LT.TEW(I)) TEMAX=TEW(I)
58    CONTINUE
      TEMIN=TEW(1)
      DO 61 I=2,365
      IF(TEMIN.GT.TEW(I)) TEMIN=TEW(I)
61    CONTINUE
      DO 63 I=1,365
      IF(TEMIN.EQ.TEW(I)) TEMD=FLOAT(I)
63    CONTINUE
      A=(TEMAX+TEMIN)/2.0
      BB=(TEMAX-TEMIN)/2.
      HS=18.3
      PI=3.14285
      DO 49 I=1,365
      TEA=A-BB*COS((2.0*PI*(FLOAT(I)-TEMD))/365.0)
      TEAS(I)=TEA
49    CONTINUE
98    DO 2 J=JC,365
      QTS=HS*(AT-TEAS(J))
      QTSS(J)=QTS
      T(1)=(B*T(2)+C*T(1)-QTS*X3)/X1
      AT=T(1)
      TAVRG=T(1)
      DO 3 I=2,N1
3     T(I)=(B*T(I-1)+B*T(I+1)+C*T(I))/X2
      TB=(B*T(N1)+C*T(N))/X1
      T(N)=TB
      JK=1
      DO 4 I=2,N
      IF(T(1)-T(I))6,6,4
6     JK=I
        TAVRG=TAVRG+T(JK)
4     CONTINUE
      IF(JK.EQ.1) GO TO 97
      T(1)=TAVRG/FLOAT(JK)
      DO 7 I=2,JK
      T(I)=T(1)
7     CONTINUE
      AT=T(1)
97    IF(CODE.LT.9.0) GO TO 80
      PRINT 101,J,(T(I),I=1,N),TEAS(J),QTS
80    IF(J.NE.1) GO TO 2
      ITR=ITR+1
      BIG=0.0
      DO 10 I=1,N
      CHECK=ABS(T(I)-TFRST(I))
      IF(BIG.LT.CHECK) BIG=CHECK
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1       CONTINUE
        IF(BIG.LT.0.0001) GO TO 99
        DO 5 I=1,N
5       TFRST(I)=T(I)
2       CONTINUE
        IF(CODE.EQ.1.) GO TO 98
        IF(CODE.GT.2.0) GO TO 77
99      CODE=10.0
        PRINT 101,J,(T(I),I=1,N),TEAS(J),QTS
        JC=2
        GO TO 98
102     FORMAT(1H ,7F9.3)
100     FORMAT(7F9.3)
77      PRINT 41,ITR
        PRINT 57,TEMAX,TEMIN,TEMD
        TOQTS1=QTSS(1)+QTSS(365)
        TOQTS2=0.0
        DO 42 I=2,364,2
        TOQTS2=TOQTS2+QTSS(I)
42      CONTINUE
        TOQTS3=0.0
        DO 46 I=3,363,2
        TOQTS3=TOQTS3+QTSS(I)
46      CONTINUE
        TOQTS=((TOQTS1+4.*TOQTS2+2.*TOQTS3)*DELTIM)/3.
        TOQTS=TOQTS/365.0
        PRINT 44,TOQTS
44      FORMAT(1X,*NET HEAT LOSS FROM THE SURFACE IN A YEAR=*,F15.5)
57      FORMAT(1X,*TEMAX=*,F7.2,4X,*TEMIN=*,F7.2,4X,*TEMD=*,F7.2)
101     FORMAT(1X,I3,17F7.2)
 41     FORMAT(1X,*ITR=*,I5)
        STOP
        END
C
$IBFTC VIBHA
        SUBROUTINE VIBHA(TE,II)
        DIMENSION TS(51),ESTS(51)
        DIMENSION POL(51)
        DIMENSION ATA(365),ARH(365),AV(365),ACF(365),ABETA(365),AQSE(365)
        DIMENSION AESTA(365)
        DIMENSION TP(51),QTSP(51),TR(51),QTSR(51)
        COMMON ATA,ARH,AV,ACF,ABETA,AQSE,AESTA
        TA=ATA(II)
        RH=ARH(II)
        V=AV(II)
        CF=ACF(II)
        BETA=ABETA(II)
        QSE=AQSE(II)
        ESTA=AESTA(II)
        TS(1)=10.
        DO 25 I=2,51
 25     TS(I)=TS(I-1)+1.
        DATA ESTS/9.204,9.839,10.512,11.225,11.982,12.781,13.628,14.524,15
       1.47,16.47,17.53,18.64,19.82,21.06,22.37,23.75,25.20,26.73,28.34,30
       2.03,31.81,33.69,35.65,37.72,39.89,42.17,44.55,47.06,49.69,52.44,55
       3.31,58.33,61.49,64.80,68.25,71.87,75.64,79.59,83.72,88.02,92.52,97
       4.54,102.10,107.21,112.53,118.06,123.83,129.85,136.11,142.62,149.4/
        DO 33 I=1,51
        T1=TS(I)
        EST1=ESTS(I)
         QBR=4.74E-08*((273.+T1)**4-BETA*(273.+TA)**4)
         QS=-(1.-0.0071*(CF**2))*QSE/24.
        QH=9.7*(0.48+0.0755*V)*(T1-TA)
        QE=19.4*(0.48+0.0755*V)*(EST1-RH*ESTA)
        AQTS=QBR+QS+QH+QE
        TR(I)=T1
        QTSR(I)=AQTS
 33     CONTINUE
        DO 100 I=1,51
        IF(QTSR(I).LT.0.0) GO TO 100
        IWNT=I
        GO TO 101
 100    CONTINUE
 101    J1=IWNT-2
        J2=IWNT
        DO 102 I=J1,J2
        POL(I)=1.0
        DO 102 J=J1,J2
        IF(I-J) 103,102,103
  103   POL(I)=POL(I)*(-QTSR(J))/(QTSR(I)-QTSR(J))
 102     CONTINUE
        TE=0.0
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      DO 104 K=J1,J2
104   TE=TE+POL(K)*TR(K)
      RETURN
      END
$ENTRY
C
C----------------------------------------------------------------------------------------------------
C
C     DETERMINATION OF TWO DIMENSIONAL VERTICAL RECIRCULATION IN THE
C     COOLING POND
C
C----------------------------------------------------------------------------------------------------
C
C     ASI IS NON-DIMENSIONAL STREAM FUNCTION
C     ASID IS DIMENSIONAL STREAM FUNCTION
C     VXN IS NON-DIMENSIONAL VELOCITY IN X-DIRECTION
C     VZN IS NON-DIMENSIONAL VELOCITY IN Z-DIRECTION
C     STEPX IS STEP SIZE IN  X-DIRECTION
C     STEPZ IS STEP SIZE IN Z-DIRECTION
C     MX IS NO OF DIVISION IN X-DIRECTION
C     NZ IS NO OF DIVISION IN Z-DIRECTION
C     MM IS TOTAL NO OF GRID POINTS IN X-DIRECTION
C     NN IS TOTAL NO OF GRID POINTS IN Z-DIRECTION
C     U IS VELOCITY AT INLET AND OUT LET
C
C*****************************************************************************
C
C                    INVISCID FLOW SOLUTION
C
C*****************************************************************************
$IBJOB
$IBFTC MAIN
      DIMENSION ASII(27,27)
      DIMENSION ASI(27,27),ASIOLD(27,27)
      DIMENSION VXN(27,27),VZN(27,27)
      READ 50,U,AL,AH,STEPX,STEPZ,MX,NZ
      PRINT 51,U,AL,AH,STEPX,STEPZ
51    FORMAT(1H0,*U=*,F8.3,*AL=*,F9.3,*AH=*,F8.3,*STEPX=*,F6.3,*STEPZ=*,
     1F6.3)
      C=(AL/AH)**2
      ITRMAX=2500
      DO 2 I=2,NZ
      DO 2 J=2,MX
      ASI(I,J)=0.0
      ASIOLD(I,J)=ASI(I,J)
2     CONTINUE
      MM=MX+1
      NN=NZ+1
      DO 3 J=1,MM
      ASI(1,J)=0.0
      ASI(NN,J)=0.0
3     CONTINUE
      DO 4 I=2,NN
      ASI(I,MM)=0.0
4     CONTINUE
      NO=NN-2
      DO 5 I=2,NZ
      ASI(I,1)=1000.0
5     CONTINUE
      ITR=0
11    ITR=ITR+1
      DO 6 J=2,MX
      DO 6 I=2,NZ
      CALL FLUN(32000)
      ASI(I,J)=(ASI(I+1,J)+ASI(I-1,J)+C*ASI(I,J+1)+C*ASI(I,J-1))/(2.+2.*
     1C)
6     CONTINUE
      BIG=0.0
      DO 8 I=2,NZ
      DO 8 J=2,MX
      DIFF=ABS(ASI(I,J)-ASIOLD(I,J))
      IF(DIFF.GT.BIG) BIG=DIFF
 8     CONTINUE
      IF(BIG.LE.0.01) GO TO 10
      DO 7 I=2,NZ
      DO 7 J=2,MX
      ASIOLD(I,J)=ASI(I,J)
7     CONTINUE
      IF(ITR.GT.ITRMAX) GO TO 10
      GO TO 11
10    PRINT 13,ITR
13    FORMAT(1H ,*THE NO OF ITERATION AT CONVERGENCE IS*,*=*,I4)
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      DO 65 I=1,NN
      DO 65 J=1,MN
      ASII(I,J)=ASI(I,J)/1000.0
65      CONTINUE
      PRINT 14
14    FORMAT(1H0,*THE VALUE OF NONDIMENSIONAL STREAM FUNCTION*,/)
      DO 18 I=1,NN
      PRINT 12,(ASII(I,J),J=1,24)
18    CONTINUE
12    FORMAT(1H0,24F5.2)
50    FORMAT(5F9.3,2I4)
      STOP
      END
$ENTRY
C
C*****************************************************************************
C
C                     CREEPING FLOW SOLUTION
C
C*****************************************************************************
$IBJOB
$IBFTC MAIN
      DIMENSION ASII(25,105)
      DIMENSION ASI(25,105),ASIOLD(25,105)
      DIMENSION VXN(25,105),VZN(25,105)
      READ 50,U,AL,AH,STEPX,STEPZ,MX,NZ
      PRINT 51,U,AL,AH,STEPX,STEPZ
51    FORMAT(1H0,*U=*,F8.3,*AL=*,F9.3,*AH=*,F8.3,*STEPX=*,F6.3,*STEPZ=*,
     1F6.3)
      C=(AL/AH)**2
      CC=(AL/AH)**4
      DA=STEPX**4
      DB=(STEPX*STEPZ)**2
      ITRMAX=1400
      DC=STEPZ**4
      BB=4.*DC+4.*C*DB
      BC=4.*DB*C+4.*CC*DA
      BD=6.*DC+8.*C*DB+6.*CC*DA
      MM=MX+1
      NN=NZ+1
      M=MX-1
      N=NZ-1
      DO 2 I=3,N
      DO 2 J=3,M
      ASI(I,J)=0.0
      ASIOLD(I,J)=ASI(I,J)
2     CONTINUE
      DO 3 J=1,MM
      ASI(1,J)=0.0
      ASI(2,J)=0.0
      ASI(NZ,J)=0.0
3     CONTINUE
      DO 4 I=3,N
       ASI(I,MX)=0.0
4     CONTINUE
      DO 5 I=3,N
      ASI(I,2)=1000.0
5     CONTINUE
      ITR=0
11    ITR=ITR+1
      DO 60 I=3,N
      ASI(I,MM)=ASI(I,M)
      ASI(I,1)=ASI(I,3)
60    CONTINUE
      DO 61 J=3,M
      ASI(NN,J)=ASI(N,J)
61    CONTINUE
      DO 6 J=3,M
      DO 6 I=3,N
      CALL FLUN(32000)
      AA=ASI(I+1,J)+ASI(I-1,J)
      AB=ASI(I+2,J)+ASI(I-2,J)
      AC=ASI(I+1,J+1)+ASI(I+1,J-1)+ASI(I-1,J+1)+ASI(I-1,J-1)
      AD=ASI(I,J+1)+ASI(I,J-1)
      AE=ASI(I,J+2)+ASI(I,J-2)
      ASI(I,J)=(BB*AA-DC*AB-2.*C*DB*AC+BC*AD-CC*DA*AE)/BD
6     CONTINUE
      BIG=0.0
      DO 8 J=3,M
       DO 8 I=3,N
      DIFF=ABS(ASI(I,J)-ASIOLD(I,J))
      IF(DIFF.GT.BIG) BIG=DIFF
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      CONTINUE
      IF(BIG.LE.0.2) GO TO 1
      IF(ITR.GE.ITRMAX) GO TO 1
      DO 7 J=3,M
      DO 7 I=3,N
      ASIOLD(I,J)=ASI(I,J)
      CONTINUE
      GO TO 11
      PRINT 13,ITR
13    FORMAT(1H ,*THE NO OF ITERATION AT CONVERGENCE IS*,*=*,I4)
      DO 65 I=1,NN
      DO 65 J=1,MM
      ASII(I,J)=ASI(I,J)/1000.0
65       CONTINUE
      PRINT 14
14    FORMAT(1H0,*THE VALUE OF NONDIMENSIONAL STREAM FUNCTION*,/)
      DO 18 I=2,NZ
      PRINT 12,(ASII(I,J),J=2,21)
18    CONTINUE
      DO 31 J=2,MX
      VXN(2,J)=(ASII(3,J)-ASII(2,J))/STEPZ
      VZN(2,J)=0.0
      VXN(NZ,J)=0.0
      VZN(NZ,J)=0.0
31    CONTINUE
      DO 32 I=2,NZ
      VZN(I,2)=0.0
      VZN(I,MX)=0.0
      VXN(I,MX)=0.0
32    CONTINUE
      DO 63 I=3,NZ
      VXN(I,2)=0.0
63    CONTINUE
      DO 20 J=3,M
      DO 20 I=3,N
      VXN(I,J)=(ASII(I+1,J)-ASII(I-1,J))/(2.*STEPZ)
20    CONTINUE
      DO 21 J=3,M
      DO 21 I=3,N
      VZN(I,J)=(ASII(I,J-1)-ASII(I,J+1))/(2.*STEPX)
21    CONTINUE
      PRINT 22
22    FORMAT(1H0,*THE VALUE OF X- COMPONENT OF VELOCITY*,/)
      DO 23 I=2,NZ
      PRINT 12,(VXN(I,J),J=2,21)
23    CONTINUE
      PRINT 24
24    FORMAT(1H0,*THE VALUE OF Z-COMPONENT OF VELOCITY*,/)
      DO 25 I=2,NZ
      PRINT 12,(VZN(I,J),J=2,21)
25    CONTINUE
50    FORMAT(5F9.3,2I4)
12       FORMAT(1H0,20F6.3)
      STOP
      END
$ENTRY
```